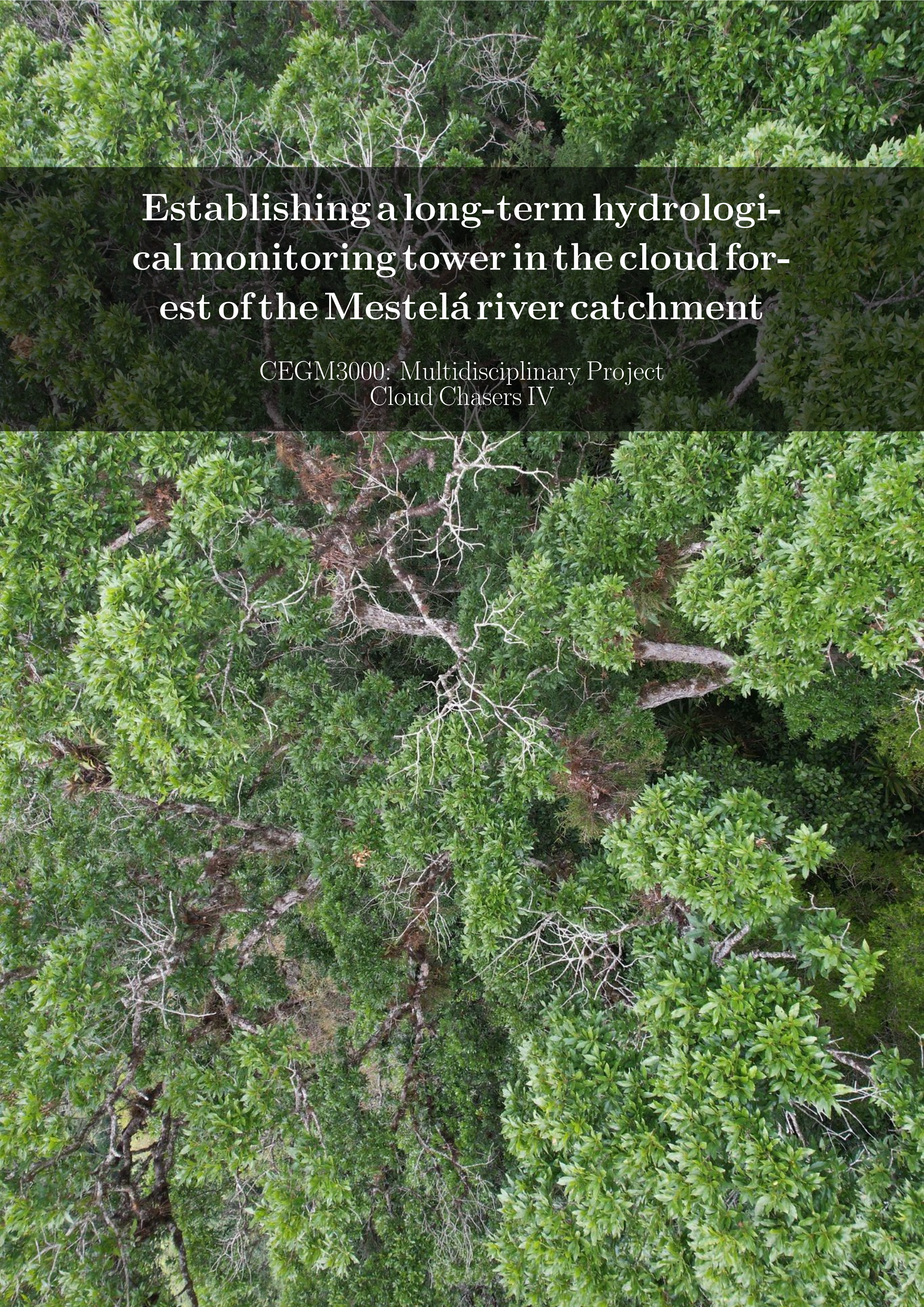
Establishing a long-term hydrological monitoring tower in the cloud forest of the Mestelá river catchment

CEGM3000: Multidisciplinary Project
Cloud Chasers IV



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Cover: Drone photograph of the Mestelá River catchment, taken by Cloud Chasers IV, 2025

1 Statement on collaboration and acknowledgements

This report was written by a team of five TU Delft master's students as first authors, all following the Multidisciplinary Project course. However, there was a close and continuous collaboration with our co-authors Sara, Yoselin, and Luis. Throughout the time in Guatemala, we worked together on a daily basis, collectively shaping both the content and direction of the project.

Beyond the core team, the full Community Cloud Forest Conservation (CCFC) team has greatly contributed to this project, a group of 15 women and of construction and agroecology professionals. Their insights, experiences, and skills were central to the process. They actively contributed through advice, mutual learning, participation in interviews and workshops, and the practical execution of the work and construction. The CCFC teachers (besides Sara and Yoselin) we want to acknowledge are Elsi, Hilda, Yolanda, Elida, Deysi, Gladys, Rosa, Sylvia, Vilma, Flori, Linsay, Cristina, Anna, and Ixchel. The construction and agroecology team consisted of Eusebio, Hector, Juan Jacicnto, Roberto, Isaias, Ismael, Miguel, Pablo y Adrian. Gracias a todos, B'antiox! Ustedes son el corazón de esta torre y proyecto.

We also wish to acknowledge Rob and Tara, the directors of CCFC, for their continuous support, thoughtful feedback, and critical engagement throughout the project. Their involvement was fundamental to the depth and direction of the work.

Finally, we are grateful to Marta and Mario, two Q'eqchi' spiritual leaders, whose wisdom and ways of thinking influenced our understanding of place, community, and responsibility within this project.

2 Statement on positionality

This report is written by four cisgender women and one cisgender man, all of white European background. We do not identify with any religious traditions and have grown up in privileged, safe, and economically secure environments. Our academic training is rooted in predominantly technical disciplines, and therefore, we approach this project from a techno-scientific perspective shaped by our education in engineering.

None of us had prior experience working with Indigenous communities, and while three group members have intermediate Spanish proficiency, two speak barely Spanish. This language barrier has limited our ability to fully engage with the local context and may have constrained the contributions of Guatemalan partners, whose perspectives had to be translated or simplified for our understanding. We acknowledge that this dynamic risks marginalising local voices and undervaluing their expertise.

Our shared identity as predominantly female researchers positively influenced collaboration with CCFC, an organisation where many team members are also women and where female empowerment is a core principle. This common ground allowed for more open communication and fostered mutual trust during the project.

At the same time, our position as white, foreign researchers inevitably created a power dynamic. We arrived with advanced tools, funding, and academic status from a prestigious European university, which can unintentionally reinforce a narrative of external "experts" bringing solutions. This perception is problematic, especially given our limited knowledge of the local ecology, culture, and institutional context. While we were often seen as "Delft engineers" capable of solving complex problems, the reality is that much of the site-specific insight, practical experience, and long-term vision came from CCFC staff and local stakeholders.

We also recognise that the short duration of this fieldwork (ten weeks) shaped our decision-making. The time pressure created a tendency to prioritise deliverables and visible outcomes over slower, more meaningful processes of engagement and reflection. While we were committed to building something of long-term value, we also had to meet academic requirements for our home university, sometimes navigating tensions between institutional expectations and local realities.

In writing this report, we aim to be transparent about the position we hold, the limitations we bring, and the assumptions we carry. Acknowledging these factors is a step toward more responsible, equitable, and reflexive collaboration and research.

3 Abstract

This multidisciplinary project, undertaken in collaboration with Community Cloud Forest Conservation (CCFC) in Alta Verapaz, Guatemala, addresses the need for long-term meteorological and hydrological monitoring in the Mestelá River catchment. The tropical montane cloud forest in this region provides essential ecosystem services through canopy cloud water interception and regulation of streamflow, yet continuous, high-quality environmental data remain limited.

To support research and conservation efforts, a 13.5 m scaffolding tower was designed and constructed as a durable, safe, and adaptable measurement platform, engineered for future extension to 25 m. The structural design accounted for local wind loads, dynamic forces, foundation stability, and corrosion resistance, ensuring a projected operational lifespan of 15 years.

Beyond infrastructure, the project developed a hydrological monitoring set-up and a Python-based modelling framework to quantify the canopy water balance and hydrological cycle. Sensor selection, placement, and integration were tailored to capture key meteorological and hydrological variables, including rainfall, fog interception, throughfall, and soil moisture. Data acquisition and storage were configured to function as autonomously as possible under remote, high-humidity cloud forest conditions, while allowing for straightforward periodic maintenance of all components involved.

Recognising that sustainability extends beyond technical performance, the project incorporated cultural and institutional engagement. Workshops and collaborative activities with CCFC staff and local stakeholders were conducted to align the monitoring system with community values, build operational capacity, and foster local ownership. A comprehensive maintenance strategy and guidelines for potential expansion were developed to ensure the continued relevance and adaptability of the system, including options for biodiversity monitoring and additional research applications.

The resulting monitoring platform combines robust engineering, scientific instrumentation, and community integration. It establishes a foundation for long-term data collection that can inform hydrological modelling, climate adaptation strategies, and evidence-based conservation, while embedding the system within the local social and ecological context.

Contents

4 Introduction

This multidisciplinary research project, conducted in collaboration with Community Cloud Forest Conservation (CCFC), focuses on the design and implementation of a 13,5-meter scaffolding tower in the cloud forest of Alta Verapaz, Guatemala. The tower is intended to serve as a long-term (15 years) structure for installing hydrological monitoring equipment. Over time, the data collected from this tower can provide valuable insights into the local hydrological cycle, support model development to anticipate future environmental changes, and contribute to data-driven environmental policy and conservation strategies.

4.1 Background and relevance

This project takes place in the catchment area of the Mestelá and Cahabón Rivers, located in Alta Verapaz, Guatemala. An overview of the catchment can be seen in Figure 1. It is an ecologically important region that provides water to the nearby city of Cobán and the surrounding Indigenous Q'eqchi' communities. The area is part of the tropical montane cloud forest, a rare and fragile ecosystem that plays a key role in regional water regulation and climate resilience.

Cloud forests have a special hydrological function due to their persistent fog cover. In addition to rainfall, they capture moisture directly from the atmosphere through a process known as cloud water interception. This allows them to store and gradually release water, which helps maintain streamflow during dry periods and reduces peak flows during heavy rainfall events. In this way, they act as natural buffers within the watershed.

These hydrological services are essential for the people living in the region. A substantial portion of the local population relies on the Mestelá River for drinking water and household use. Maintaining the health of the forest ecosystem is therefore directly related to water security and the quality of life of nearby communities.

Despite its importance, long-term hydrological monitoring of cloud forests in this region is limited. The implementation of monitoring technology in remote, resource-constrained areas like Alta Verapaz often faces several challenges: financial limitations, a lack of technical maintenance capacity, and insufficient integration with local stakeholder needs and knowledge systems. Yet, improving local understanding of water dynamics is essential, not only for ecological conservation but also for protecting livelihoods and securing sustainable development pathways.

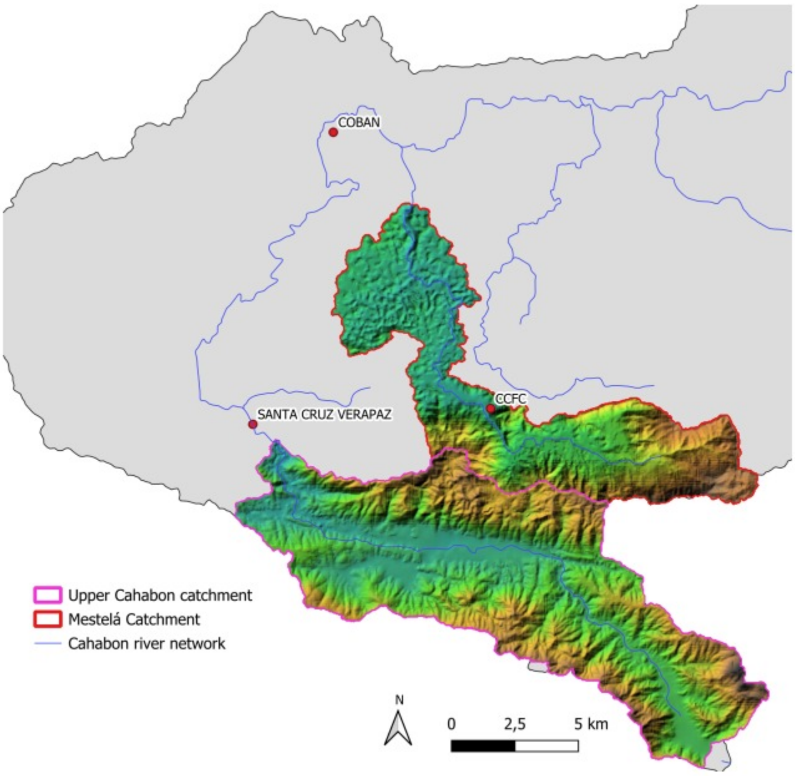

Figure 1: Mestelá and Cahabón river catchment (Hiemstra 2024)

4.2 Project motivation and scope

Building on the previous Cloud Chasers projects, which initiated hydrological monitoring in the area, this study aims to address some of the key shortcomings that hampered its long-term effectiveness, such as equipment degradation and the lack of a robust maintenance plan. The idea for a permanent scaffolding structure originated from CCFC, based on their desire to create a durable and functional structure for high-quality environmental data collection. Furthermore, the tower offers opportunities for other types of research projects, such as biological monitoring or bird acoustics.

Our role as a multidisciplinary student team was to further develop this idea, designing the set-up, physically constructing the tower, and ensuring it is integrated with both local projects and scientific goals. In doing so, we seek to bridge engineering, environmental science, and stakeholder engagement.

4.3 Research objective and questions

Given the context, motivation and scope, the central research question guiding this multidisciplinary project is:

"How can the design and implementation of a long-term hydrological monitoring tower in the cloud forest of the Mestelá River catchment support both effective hydrological data collection and sustainable local ownership?"

This research question is broad and complex, reflecting the multifaceted nature of the challenge. Addressing it requires attention not only to technical implementation, but also to stakeholder collaboration, ecological relevance, and long-term impact. Therefore, we translated this overarching question into four specific, interconnected project objectives that guide our work:

1. Construct a 13.5-meter scaffolding tower that is safe and functional as a long-term location for hydrological measurement in the Mestelá cloud forest.
   This objective focuses on the physical realisation of the monitoring infrastructure. Safety, durability, and functionality were core criteria during the design and construction phases.
2. Develop a long-term hydrological monitoring set-up and compatible model that enhances knowledge of the canopy water balance and hydrological cycle.
   Beyond the tower itself, this goal addresses the installation and integration of hydrological sensors and data processing tools, enabling meaningful environmental analysis.
3. Understand and communicate the role and perceived value of the monitoring system within the cultural and ecological context of CCFC and its stakeholders.
   Long-term sustainability depends not only on technical design but also on local ownership and relevance. This objective focuses on ensuring that the monitoring system is meaningful to those who will use and maintain it, aligning it with local values, priorities, and capacities.
4. Provide recommendations for the system's future maintenance, communication, and potential expansion, supporting long-term impact and further research.
   This final objective links everything together: it ensures the monitoring set-up will remain operational and relevant over time by embedding it within a strategy for continuity, co-ownership, and future development.

4.4 Report structure

This report is structured around the four project objectives. Each chapter provides a detailed introduction, methodology, results, discussion, and conclusion for one of the objectives. The report concludes with an integrated reflection and recommendations for future multidisciplinary efforts in similar contexts.

5 Objective A: Tower construction

5.1 Introduction

The goal of the monitoring tower is to enable long-term, reliable data collection within the cloud forest of the Mestelá River catchment. To serve this purpose, the structure must be safe, stable, and adaptable, providing sufficient height to reach various levels within the forest canopy and flexibility to host various hydrological sensors and instruments. This chapter outlines the design and construction of a 13.5-meter scaffolding tower that meets these requirements and supports future research and monitoring efforts.

5.2 Site selection and description

5.2.1 Site selection process

The selection of a suitable measurement location was guided by advice from the Cloud Chasers II group, who compared three potential sites, Hillside CCFC, Mount Xucaneb and Brecha, based on factors such as altitude, cloud interception, accessibility, internet connection and safety (Boot et al. 2023). Hillside CCFC was ultimately recommended as the most promising location due to its proximity to the CCFC campus, guaranteed internet access, typical altitude and ease of maintenance.

Based on this recommendation, the previous measurement site at Hillside CCFC was revisited. In collaboration with the CCFC team, nearby locations that fulfilled the original criteria while offering additional advantages for tower installation were evaluated. Unlike the earlier site, which was optimised for in-tree equipment, the new set-up required enough space to install a tower without damaging nearby vegetation too much and with a relatively level base to ensure safe construction.

The final site was selected together with the CCFC team, whose ecological knowledge and familiarity with the cloud forest were essential in evaluating suitability. The chosen location balances the ecological representativeness of the forest with the practical requirements of tower installation. One side of the site is bordered by dense forest, enabling accurate in-canopy measurements, while the other side opens up just enough to ensure sufficient sunlight reaches the solar panel, addressing an important issue identified after the previous group, where low light conditions affected energy supply.

5.2.2 Site description

The selected site is located at an altitude of 1669 meters, with coordinates 15°22'08.7"N, 90°20'42.9"W, shown in Figure 2. Using drone measurements, the canopy height was determined to start at 13 meters, with the tallest trees reaching approximately 24 meters, guiding the tower height for both in-canopy and above-canopy measurements.

Figure 2: Overview of measurement site location (Google Earth, 2025)

The area around the tower offers sufficient space for the tower itself, throughfall equipment and soil sensors. The terrain is relatively flat, reducing the need for additional foundation adjustments. The site orientation and surrounding vegetation allow for effective fog interception and throughfall measurement on the forest-facing side, while maintaining solar exposure on the open side for uninterrupted power supply to the equipment. Figure 3 shows a drone-captured top view of the selected location.

Figure 3: Top view of measurement site location (Cloud Chasers IV, 2025)

5.3 Design requirements

As outlined in Subsection 5.2, the monitoring tower is intended to support measurement equipment at two levels: a minimum of 24 meters (above the canopy) and a minimum of 13 meters (within the canopy). The current implementation is limited to 13.5 meters due to budget and time constraints, and in accordance with the client's preferences. However, the entire structural design and all calculations are based on a 25-meter tower. This means that the tower is already dimensioned and engineered for the full height, ensuring that future expansion to 25 meters can be carried out without redesign or major structural modifications. This approach supports long-term flexibility. The following set of requirements provides the basis for the current 13.5-meter set-up while enabling the future expansion:

- The monitoring structure provides sufficient space and mounting points for in-canopy measurements at heights of up to at least 13 meters.
- The monitoring structure provides sufficient space and mounting points for additional future research equipment, with the capability to be positioned up to at least 13 meters.
- The monitoring structure supports the provisioned installation of monitoring equipment at a height of at least 24 meters for above-canopy measurements in the future.
- The foundation is capable of supporting the total weight of the tower, equipment and three persons during maintenance.
- The monitoring structure is able to resist dynamic loads, such as wind gusts and vibrations, ensuring minimal movement or resonance.
- The construction materials are able to resist corrosion, wildlife damage and environmental wear.
- The monitoring structure has a minimum lifespan of 15 years without significant degradation.
- The monitoring structure ensures that all components are easily accessible for routine maintenance.
- A lightning protection system is incorporated to mitigate the risk of electrical storms damaging the monitoring structure and its components.

5.4 Design process

A scaffolding tower of 13.5 meters for the in-canopy measurements is chosen for its ability to provide a stable, elevated platform that ensures sufficient space for sensor placement and accessibility for maintenance. The tower consists of nine levels, each 1.5 meters in height, and has a base width of 1.5 meters by 1.45 meters. For the above canopy measurements in the future, a pole in the centre of the tower is selected, as there is insufficient space to accommodate a full 25-meter tower. This design also offers material savings while still ensuring that the sensors for above-canopy measurements can be positioned effectively.

The monitoring tower is equipped with a ladder at two sides to facilitate easy maintenance. Additionally, a lifting mechanism must be designed to raise the equipment along the upper section of the pole, starting from the height of the tower, 13.5 m, up to the top of the pole at 25 m. However, the design of this mechanism is outside the scope of this study, as the focus is on the tower construction, and it does not impact the overall tower design and structural calculations.

The overall design is shown in Figure 4, and the measurements of all tower components are shown in Appendix A. This section outlines the structural calculations, which were performed in Excel[1].

5.4.1 Structural forces

On the tower, two forces dominate. These consist of the dead-weight of the structure and the wind load.

[1] Excel available at: https://docs.google.com/spreadsheets/d/1bsZ0tOHr5aV1i6uc1nKeBybDjzbpsqg7q3lrt8ucZEA/copy

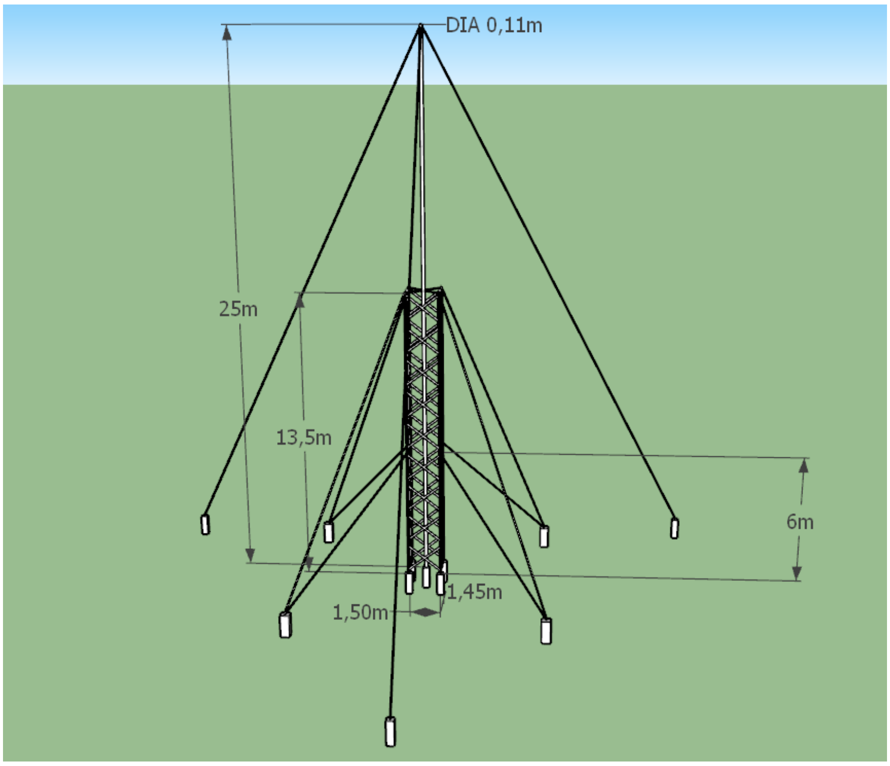

Figure 4: Sketch of the measurement tower

Dead-load
The pole of the structure consists of a hollow steel pipe. Formula 1 shows the calculation of the pole dead-weight, W_p. The weight of the sensors is also included in the weight of the pole, and is assumed to be 50 kg. This value is conservative to provide flexibility for additional future sensors.

The tower is constructed using two main components: a ladder section on two sides and a diagonal section on the other two sides. The dead weight of the tower is determined by weighing both the ladder and diagonal sections and multiplying their respective weights by the number of each component used in the tower's construction. The weight of three persons, each assumed to be 100 kg, and the weight of sensors, assumed to be 50 kg, are added to this dead weight. This total weight of the tower is in Formulas 2 represented as W_t.

$$W_p = (\pi(r_{o,p}^2 - r_{i,p}^2) \cdot l_p \cdot \rho_{steel}) + W_{sensors} \quad (1)$$

Where:

$$\begin{aligned} W &= \text{Dead-weight [kg]} \\ r_o &= \text{Outer radius [m]} \\ r_i &= \text{Inner radius [m]} \\ l &= \text{Length [m]} \\ \rho_{\text{steel}} &= \text{Density of steel [kg/m}^3\text{]} \end{aligned}$$

Formulas 2 can then be used to calculate the dead-load of the pole and the tower.

$$
\begin{aligned}
\mathrm{F_{d,t}} &= W_t \cdot g \cdot FoS \\
\mathrm{F_{d,p}} &= W_p \cdot g \cdot FoS
\end{aligned}
\tag{2}
$$

Where:

F_d = Dead-load [N]
W_t = Dead-weight tower [kg]
W_p = Dead-weight pole [kg]
g = Acceleration due to gravity [m/s^2]
FoS = Factor of Safety [−]

When the weight of the pole works positively for the distribution of the forces, it is multiplied by a Factor of Safety of *0.9*. When it works negatively, it is multiplied by a Factor of Safety of *1.2* (Soons and van Raaij 2014).

Wind load with the Eurocode
The wind load for the scaffolding tower is determined with Eurocode 3: Design of steel structures - Part 3-1: Towers, masts and chimneys - Towers and masts (Nederlands Normalisatie Instituut 2011).

For these calculations, a critical wind load should be chosen. The wind velocity has been determined with Figure 5. Figure 5 shows that the monitoring set-up's location experiences a wind pressure of 0.48 kg/m^2 with a return period of 50 years (Dlubal Software 2023). The wind velocity is then around 30 m/s. With this wind pressure, a high level of safety is ensured for a monitoring set-up with a lifespan of 15 years. According to the Eurocode, wind pressures are additionally multiplied by a Factor of Safety of 1.5, which can be found in Table A.1.8. of Eurocode - Basis of structural and geotechnical design. In this Table, an unfavourable variable action for verification case VC1 is chosen. VC1 is used for both structural and geotechnical designs (*NEN-EN 1990: Eurocode — Basis of structural and geotechnical design* 2023).

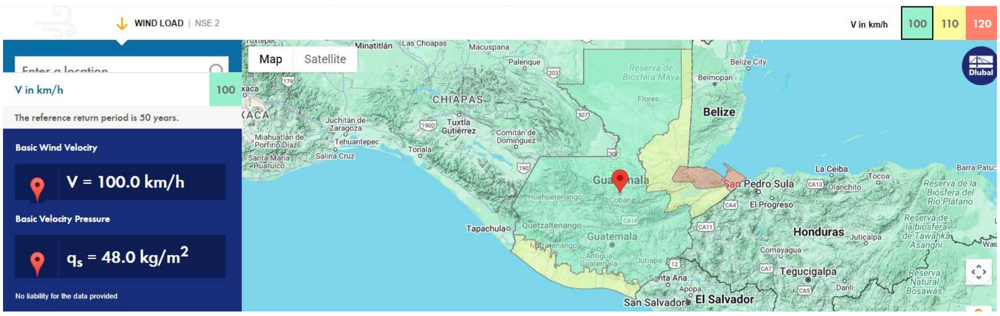

Figure 5: Wind pressure Guatemala (Dlubal Software 2023)

Wind force coefficients
The total wind force coefficient c_f in the direction of the wind over a section of the structure should be taken, as represented in Formula 3.

$$
c_f = c_{f,s} + c_{f,A} + c_{f,G} \tag{3}
$$

Where:

$c_{f,s}$ = The wind force coefficient of the scaffolding tower section $[-]$
$c_{f,A}$ = The wind force coefficient of the ancillaries (the pole) $[-]$
$c_{f,G}$ = The wind force coefficient normal to the guy wires in the plane $[-]$

First $c_{f,s}$ for the scaffolding tower is calculated with Formulas 4.

$$\begin{aligned} c_{f,s} &= K_\theta \cdot c_{f,s,0} \\ K_\theta &= 1 + K_1 K_2 \sin^2 2\theta \\ K_1 &= \frac{0.8A_c}{A_S} \\ K_2 = \phi &= \frac{A_{\text{tower}}}{A_{\text{rigid tower}}} \\ c_{f,s,0} &= c_{f,0,c} \cdot \frac{A_c}{A_S} \\ c_{f,0,c} &= C_1(1 - C_2\phi) + (C_1 + 0.875)\phi^2 \end{aligned} \tag{4}$$

Where:

θ = Angle of incidence of the wind normal to the face [°]
A_c = Projected area of the circular-section members in sub critical regimes [m^2]
A_s = Projected area of all the members [m^2]
ϕ = Solidity ratio $[-]$
C_1 = 2.25 for square structures $[-]$
C_2 = 1.5 for square structures $[-]$

The angle of incidence of the wind normal to the face is chosen to be 0°, because this results in the largest wind load, making it the critical scenario. Formulas 4 have been simplified, since the construction of the scaffolding tower only consists of circular section members in the sub-critical regime, which has been determined with Formula 5 and a wind velocity of 30 m/s. There are no flat-sided members present in the construction, and also no circular section members in the supercritical regime. Therefore, for this construction, $A_S = A_c$. The complete formulas taken from the Eurocode can be found in Appendix B (Nederlands Normalisatie Instituut 2011).

$$Re = \frac{V \cdot D}{\nu} \tag{5}$$

Where:

Re = Reynolds number $[-]$
V = Wind velocity [m/s]
D = Diameter of the circular sections [m]
ν = The kinematic viscosity of the air [m^2/s]

Next, $c_{f,A}$, the wind force coefficient of the ancillaries, is determined in Formula 6. For this construction, the middle pole of 25 meters is specified as an ancillary. This pole is also a circular section in the sub-critical regime, calculated with the Reynolds number.

$$c_{f,A} = c_{f,A,0} \cdot K_A \sin^2 \psi \tag{6}$$

Where:

K_A = Reduction factor for shielding (No shielding: 1.0) [−]

ψ = The angle of wind incidence to the longitudinal axis of any linear member [90°]

$c_{f,A,0}$ = 1.2 (Circular section with $\mathrm{Re} \leq 2 \cdot 10^5$, (Nederlands Normalisatie Instituut 2011)) [−]

In this calculation, the shielding of the pole by the structure is minimal, so the K_A is determined to be 1.0. The angle of the wind incidence is set to be 90°, the wind is then normal to the pole, which leads to the critical scenario. The coefficient $c_{f,A,0}$ is determined in accordance with Table B.2.1 of the Eurocode (Nederlands Normalisatie Instituut 2011).

At last, the wind force coefficient of the guy wires is determined, $c_{f,G}$.

$$c_{f,G} = c_{f,G,0} \sin^2 \psi$$

Where:

ψ = The angle of wind incidence to the chord [45°]

$c_{f,G,0}$ = 1.3 (1×7 spiral steel strand, $\mathrm{Re} \leq 4 \cdot 10^4$, Nederlands Normalisatie Instituut 2011) [−]

When the wind is normal to the face of the scaffolding tower, it has an angle of wind incidence to the guy wires of 45°. The coefficient $c_{f,G,0}$ can be determined with the mechanical specifics of the guy wires and the Reynolds number, in accordance with Table B.2.1 of the Eurocode (Nederlands Normalisatie Instituut 2011).

Wind loads
When the wind force coefficients of the pole, scaffolding tower and the guy wires have been determined, the wind loads can be calculated according to Formulas 7. The wind load is first calculated over the full projected surface area of each component using the wind pressure formula. This is essential because components like the scaffolding have complex geometries that differ from rigid walls. To obtain a distributed load (in kN/m), this total force is then divided by the height or length of the component. For the guy wires, the shortest wire length is used to yield a conservative estimate of the wind load per meter.

$$\begin{aligned} q_{w,p} &= \frac{\frac{1}{2}\rho V^2 c_{f,A} \cdot A_{pole}}{l_{pole}} \\ q_{w,t} &= \frac{\frac{1}{2}\rho V^2 c_{f,s} \cdot A_{tower}}{l_{tower}} \\ q_{w,w} &= \frac{\frac{1}{2}\rho V^2 c_{f,G} \cdot A_{wires}}{l_{wire}} \end{aligned} \tag{7}$$

Where:

q = Wind loads [N/m]

ρ = Density of air (1.25 [kg/m^3])

V = Wind velocity (30 [m/s])

C_f = Wind force coefficients [−]

The results of the calculations in this paragraph are shown in Table 1, which also includes the Factor of Safety.

Parameter	Value	Unit
W_p	775	kg
W_t	818	kg
$F_{d,p}$ positive	6.8429	kN
$F_{d,t}$ positive	7.2221	kN
$F_{d,p}$ negative	9.1239	kN
$F_{d,t}$ negative	9.6295	kN
$q_{w,p}$	0.0743	kN/m
$q_{w,t}$	0.2227	kN/m
$q_{w,w}$	0.0240	kN/m

Table 1: Structural forces

5.4.2 Structural diagrams and calculations pole

Structural scheme

For stabilisation and structural safety of the pole, all forces working on the pole are determined in Figure 6. The force of the tower wires, which attach the pole to the tower for more stabilisation, is also taken into account as $F_{wire,2}$. Formulas 8 are used to calculate the forces on the pole.

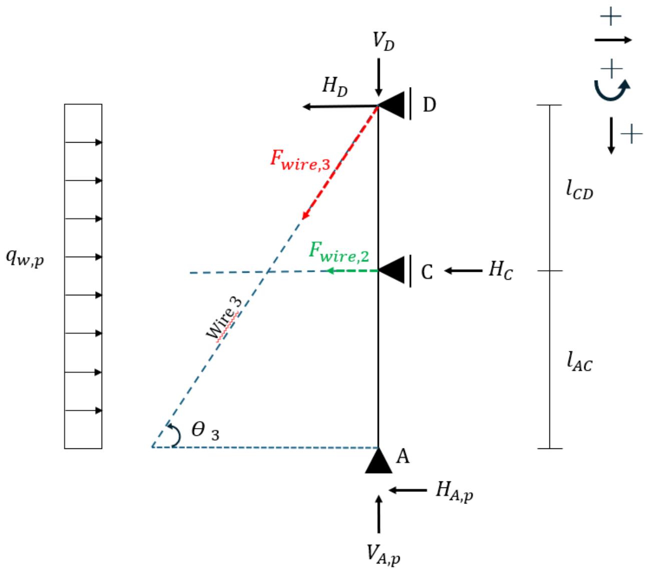

Figure 6: Structural scheme pole

$$
\begin{aligned}
H_D &= \frac{1}{2} q_{w,p} l_{CD} \\
H_C = F_{wire,2} &= \frac{1}{2} q_{w,t} l_{BC} + \frac{1}{2} q_{w,p} l_{AC} + \frac{1}{2} q_{w,p} l_{CD} \\
H_{A,p} &= \frac{1}{2} q_{w,p} l_{AC} \\
V_D &= \tan(\theta_3) \cdot H_D \\
V_{A,p} &= F_{d,p} + \tan(\theta_3) \cdot H_D \\
F_{wire,3} &= \frac{H_D}{\cos(\theta_3)}
\end{aligned} \tag{8}
$$

Where:

H = Horizontal force [kN]
$q_{w,p}$ = Wind load per unit length [kN/m]
$F_{d,p}$ = Dead-load pole [kN]
l = Length [m]
F_{wire} = Force from wire [kN/m]
V = Vertical force [kN/m]
θ = Force angle [rad]

Moment Diagram
To calculate M_C, the 'hoekmethode' (angle method) is used to relate the internal rotations at different points along the pole, shown in Figure 7.

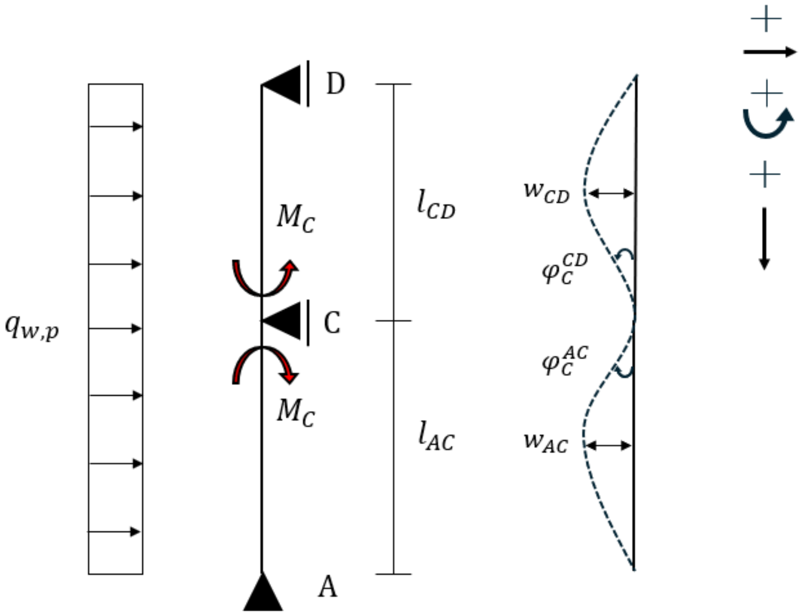

Figure 7: 'Hoekmethode' M_C total

By calculating both angular displacements ϕ_C^{AC} and ϕ_C^{CD}, the 'vormveranderingsvoorwaarde' (condition of compatibility of deformations) can be applied, stating that the angular displacements ϕ_C^{AC} and ϕ_C^{CD} must be equal. Figure 8 shows how ϕ_C^{AC} is calculated. Figure 9 shows how ϕ_C^{CD} is calculated. Rewriting gives the formula for M_C, as shown in Formulas 9.

To find the moments at the midpoints of spans AC and CD, the total moment at support C can be superposed with the moment distributions due to the distributed loads on AC and CD. This leads to Formulas 10, and is also graphically represented in Figure 10.

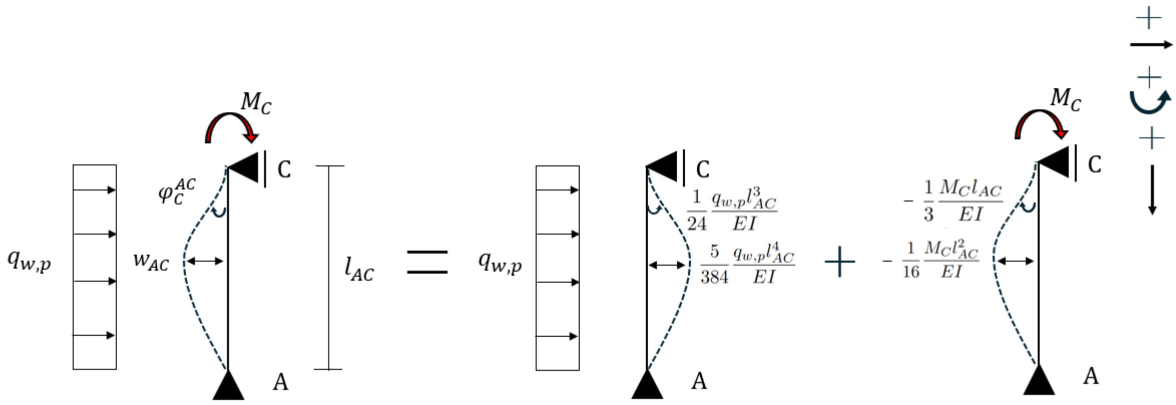

Figure 8: 'Hoekmethode' AC

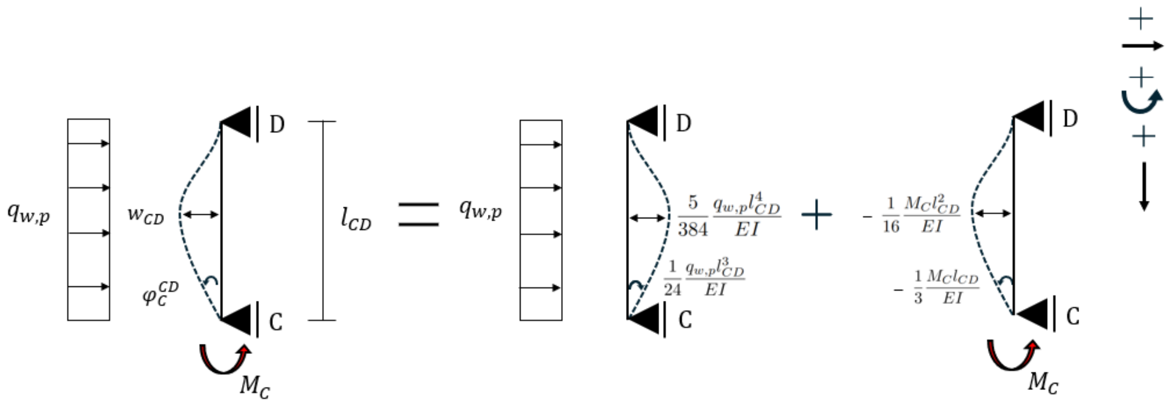

Figure 9: 'Hoekmethode' CD

$$
\begin{aligned}
\phi_C^{CD} &= \phi_C^{AC} \\
\frac{1}{24}\frac{q_{w,p}l_{CD}^3}{EI} - \frac{1}{3}\frac{M_C l_{CD}}{EI} &= \frac{1}{24}\frac{q_{w,p}l_{AC}^3}{EI} - \frac{1}{3}\frac{M_C l_{AC}}{EI} \\
M_C(l_{AC} + l_{CD}) \cdot 24EI &= (q_{w,p}l_{CD}^3 + q_{w,p}l_{AC}^3) \cdot 3EI \\
M_C &= \frac{1}{8}q_{w,p}(l_{CD}^2 + l_{AC}^2)
\end{aligned} \tag{9}
$$

$$
\begin{aligned}
M_{AC} &= \frac{M_C}{2} - \frac{1}{8}q_{w,p}l_{AC}^2 \\
M_{CD} &= \frac{M_C}{2} - \frac{1}{8}q_{w,p}l_{CD}^2
\end{aligned} \tag{10}
$$

Where:

$$\begin{aligned} \phi &= \text{Angular displacement [rad]} \\ q_w &= \text{Wind load per unit length [kN/m]} \\ l &= \text{Length [m]} \\ E &= \text{Young's modulus [N/m}^2\text{]} \\ I &= \text{Moment of inertia [m}^4\text{]} \\ M &= \text{Moment [kNm]} \end{aligned}$$

In total, this results in the moment diagram for the pole as shown in Figure 10.

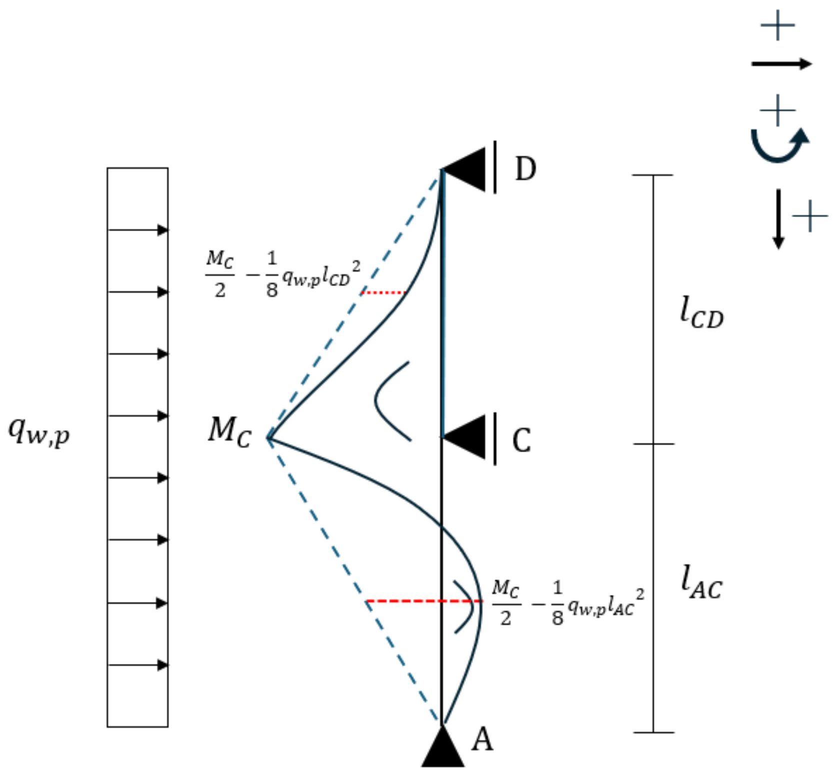

Figure 10: Moment diagram pole

Deflection
From Figure 8, the maximum deflection in l_{AC} is derived. From Figure 9, the maximum deflection in l_{CD} is derived. These calculations indicate that the pole's deflection is the governing factor, and by limiting the maximum allowable deflection, the resulting outer radius and inner radius are determined through an iterative process. The maximum deflection is calculated in Formulas 11.

$$
\begin{aligned}
w_{AC} &= \frac{5}{384}\frac{q_{w,p}l_{AC}^4}{EI} - \frac{1}{16}\frac{M_C l_{AC}^2}{EI} \\
w_{CD} &= \frac{5}{384}\frac{q_{w,p}l_{CD}^4}{EI} - \frac{1}{16}\frac{M_C l_{CD}^2}{EI} \\
I &= \frac{1}{4}\pi \cdot (\mathrm{r}_{\mathrm{o,p}}^4 - \mathrm{r}_{\mathrm{i,p}}^4) \\
w_{AC} &< \frac{l_{AB}}{1000} \\
w_{CD} &< \frac{l_{CD}}{1000}
\end{aligned} \tag{11}
$$

Where:

w = Deflection [m]
q_w = Wind load per unit length [kN/m]
l = Length [m]
I = Moment of Inertia [m^4]
$r_{o,p}$ = Outer radius [m]
$r_{i,p}$ = Inner radius [m]

The maximum deflection that is allowed in between guy levels is L/1000. This has been found in section F.4.2.2 of Eurocode 3: Ontwerp en berekening van staalconstructies - Deel 3-1: Torens, masten en schoorstenen - Torens en masten (Nederlands Normalisatie Instituut 2025).

Stresses
With the moment and normal force, the resulting stresses in the pole can be calculated. The pole's slender geometry results in a relatively small cross-sectional area and moment of inertia, which can cause high stress and deflection due to the exposure of wind loads. These stresses must be checked to ensure structural safety. The resulting stresses should be lower than the maximum allowable stress of the type of steel that is used for the pole.

Bending stress
With the largest moment M_C acting on the pole, as calculated in Figure 10, the resulting bending stress $\sigma_{\text{bending,xx}}$ can be calculated. This is the stress in the wind direction (x-direction), due to bending about the axis perpendicular to the wind. Since bending stresses are greatest at the outermost fibres of the cross section, the distance x is taken as the outer radius of the pole. The bending stress is hence calculated as in Formula 12. The allowable bending stress in the outermost fibre is calculated with the yield strength of the steel of the pole (275 MPa) as shown in Formula 13, where the material Factor of Safety is taken to be 1.5 (Soons and van Raaij 2014).

$$
\begin{aligned}
\sigma_{\text{bending,xx}} &= \frac{\mathrm{M}_{xx} \cdot x}{\mathrm{I}_{xx}} \\
\mathrm{I}_{xx} &= \frac{1}{4}\pi \cdot (\mathrm{r}_{\mathrm{o,p}}^4 - \mathrm{r}_{\mathrm{i,p}}^4) \\
\mathrm{M}_{xx} &= M_C \\
x &= \text{Perpendicular distance from the neutral axis} = \mathrm{r}_{\mathrm{o,p}}
\end{aligned} \tag{12}
$$

$$
\begin{aligned}
\sigma_{\text{bending,xx,allowable}} &= \frac{f_y}{\gamma_m} \\
\sigma_{\text{bending,xx}} &< \sigma_{\text{bending,xx,allowable}}
\end{aligned} \tag{13}
$$

Where:

σ_{xx} = Bending stress [MPa]
I_{xx} = Moment of Inertia [m^4]
$r_{o,p}$ = Outer radius [m]
$r_{i,p}$ = Inner radius [m]
f_y = Yield strength of steel [MPa]
γ_m = Material Factor of Safety [−]

Normal stress
The axial force results in a normal stress across the cross-section. The stress must remain below the allowable stress to prevent failure under compression. For the axial force, the vertical force of the tension in the wires is calculated, plus the dead-weight of the pole. This is the force $V_{A,p}$ as shown in Figure 6. The normal stress is hence calculated as in Formulas 14. The allowable normal stress is also calculated with the yield strength of the steel of the pole (275 MPa), as shown in Formulas 15, where the material Factor of Safety is taken to be 1.5 again (Soons and van Raaij 2014).

$$\sigma_{\text{normal}} = \frac{N}{A_p} \tag{14}$$

$$N = V_{A,p}$$

$$A_p = \pi \cdot (\mathrm{r}_{\mathrm{o,p}}^2 - \mathrm{r}_{\mathrm{i,p}}^2)$$

$$\sigma_{\text{normal,allowable}} = \frac{f_y}{\gamma_m} \tag{15}$$

$$\sigma_{\text{normal}} < \sigma_{\text{normal,allowable}}$$

Where:

σ_{normal} = Normal stress [MPa]
N = Axial force [kN]
A_p = Cross-sectional area of pole [m^2]
$r_{o,p}$ = Outer radius [m]
$r_{i,p}$ = Inner radius [m]
f_y = Yield strength of steel [MPa]
γ_m = Material Factor of Safety [−]

Buckling
The pole of the tower is tested for buckling. This is done with Eurocode 3 - Design of steel structures - Part 1-1: General rules and rules for buildings (Nederlands Normalisatie Instituut 2025). First, the relative slenderness of the pole is calculated, as shown in Formulas 16. The buckling length is chosen as the longest unsupported length of the pole, which is l_{AC}. The yield strength depends on the type of steel that is used for the pole, taken to be 275 MPa again. The modulus of elasticity is taken to be 210,000 MPa.

$$\bar{\lambda} = \frac{L_{\text{cr}}}{i}\frac{1}{\lambda_1} \tag{16}$$

$$\lambda_1 = \pi \cdot \sqrt{\frac{E}{f_y}}$$

$$\mathrm{L}_{cr} = \mathrm{l}_{AC}$$

Where:

$\bar{\lambda}$ = Relative slenderness [−]
L_{cr} = Buckling length [m]
E = Young's Modulus (Modulus of Elasticity) [MPa]
f_y = Yield strength of steel [MPa]
i = Radius of gyration [m]

With the relative slenderness $\bar{\lambda}$, ϕ can be calculated for the buckling reduction factor χ. These are shown in Formulas 17. The imperfection factor α is determined with Table 8.3 of the Eurocode 3 (Nederlands Normalisatie Instituut 2025), where the most conservative value of 0.49 has been chosen, since the imperfection factor α depends on the type of steel, and whether it is hot finished or cold-formed.

$$\phi = 0.5\left[1 + \alpha\left(\bar{\lambda} - 0.2\right) + \bar{\lambda}^2\right] \quad (17)$$
$$\chi = \frac{1}{\phi + \sqrt{\phi^2 - \bar{\lambda}^2}}$$

Where:

α = Imperfection factor [−]
χ = Buckling reduction factor [−]

Now that the buckling reduction factor χ is known, the design buckling resistance $N_{b,Rd}$ can be calculated, with a safety factor γ_{M1}. Where γ_{M1} is the partial factor for resistance of members to instability assessed by member checks (Nederlands Normalisatie Instituut 2025). N_{Rk} is the characteristic value of the resistance to compression, which can be calculated with the surface of the cross-section of the pole and the yield strength of the steel. All of this is shown in Formulas 18.

$$N_{b,Rd} = \frac{\chi \cdot N_{Rk}}{\gamma_{M1}} \quad (18)$$
$$N_{Rk} = A \cdot f_y$$

Where:

$N_{b,Rd}$ = Design buckling resistance [kN]
N_{Rk} = Characteristic resistance of the steel [kN]
γ_{M1} = Safety factor [−]
A = Surface of cross section pole [m^2]
f_y = Yield strength of the steel [MPa]

Now that the design buckling resistance is calculated, the buckling can be tested with the compressive force on the pole. This is shown in Formulas 19.

$$\frac{N_{ED}}{N_{b,Rd}} \leq 1 \quad (19)$$
$$N_{ED} = V_D + F_{d,p}$$

Where:

N_{ED} = Axial force [kN]

The ratio of the design buckling resistance and the axial force on the pole should be smaller than or equal to 1 for a safe design.

The results of the calculations in this paragraph are shown in Table 2.

Parameter	Value	Unit
H_D	0.6404	kN
H_C	2.6448	kN
$H_{A,p}$	0.7518	kN
V_D	1.1092	kN
$V_{A,p}$	9.8529	kN
$F_{\text{wire},2}$	2.6448	kN
$F_{\text{wire},3}$	1.2808	kN
M_C	4.3784	kNm
M_{AC}	-0.3480	kNm
M_{CD}	0.3480	kNm
w_{AC}	-0.0018	m
$l_{AB}/1000$	0.0135	m
w_{CD}	-0.0115	m
$l_{CD}/1000$	0.0115	m
σ_{bending}	53.4932	MPa
σ_{normal}	2.9671	MPa
$\sigma_{\text{allowable}}$	183	MPa
$N_{b,\text{rd}}$	40.5482	kN
N_{rk}	1015.9911	kN

Table 2: Structural Calculations Pole

5.4.3 Structural diagrams and calculations tower

Structural scheme

For the stabilisation and structural safety of the tower, all the forces working on the tower are determined in Figure 11. A force from the wires from the pole, $F_{wire,2}$, is also taken into account. Formulas 20 are used to calculate the forces on the pole.

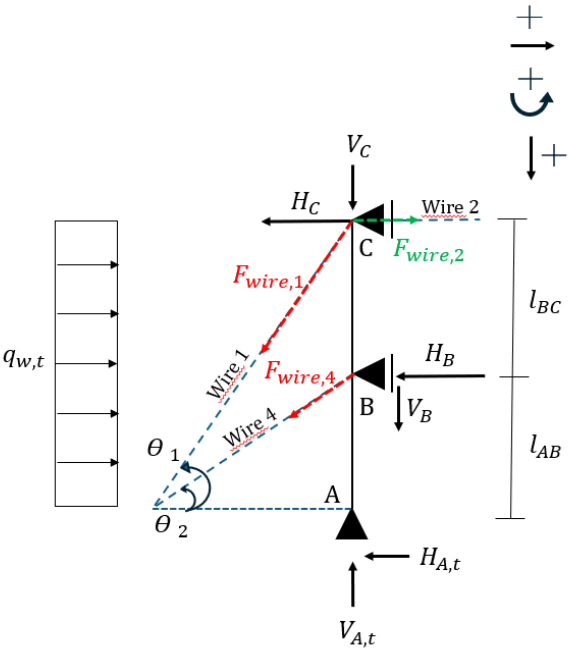

Figure 11: Structural scheme tower

$$
\begin{aligned}
H_C = F_{wire,2} &= \frac{1}{2}q_{w,t}l_{BC} + \frac{1}{2}q_{w,p}l_{AC} + \frac{1}{2}q_{w,p}l_{CD} \\
H_B &= \frac{1}{2}q_{w,t}l_{AB} + \frac{1}{2}q_{w,t}l_{BC} \\
H_{A,t} &= \frac{1}{2}q_{w,t}l_{AB} \\
V_C &= tan(\theta_1) \cdot H_C \\
V_B &= tan(\theta_2) \cdot H_B \\
V_{A,t} &= F_{d,t} + tan(\theta_1) \cdot H_C + tan(\theta_2) \cdot H_B \\
F_{wire,1} &= \frac{H_C}{\cos(\theta_1)} \\
F_{wire,4} &= \frac{H_B}{\cos(\theta_2)}
\end{aligned} \tag{20}
$$

Where:

H = Horizontal force [kN]
$q_{w,p}$ = Wind load per unit length [kN/m]
l = Length [m]
F_{wire} = Force from wire [kN/m]
V = Vertical force [kN/m]
θ = Force angle [rad]
F_d = Dead force [kN/m]

Moment diagram
To calculate M_B, the 'hoekmethode' (angle method) is used again to relate the internal rotations at different points along the pole, as shown in Figure 12.

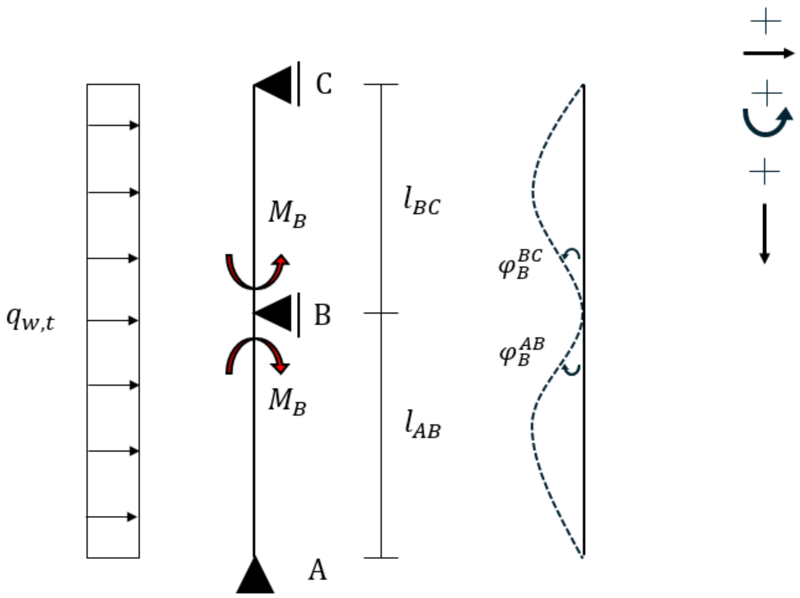

Figure 12: 'Hoekmethode' M_B total

By calculating both angular displacements ϕ_B^{AB} and ϕ_B^{BC}, the 'vormveranderingsvoorwaarde' (condition of compatibility of deformations) can be applied, stating that the angular displacements ϕ_B^{AB} and ϕ_B^{BC} must be equal. Figure 13 shows how ϕ_B^{AB} is calculated. Figure 14 shows how ϕ_B^{BC} is calculated. Rewriting gives the formula for M_B, as shown in Formulas 21.

To find the moments at the midpoints of spans AB and BC, the total moment at support B can be superposed with the moment distributions due to the distributed loads on AB and BC. This leads to Formulas 22.

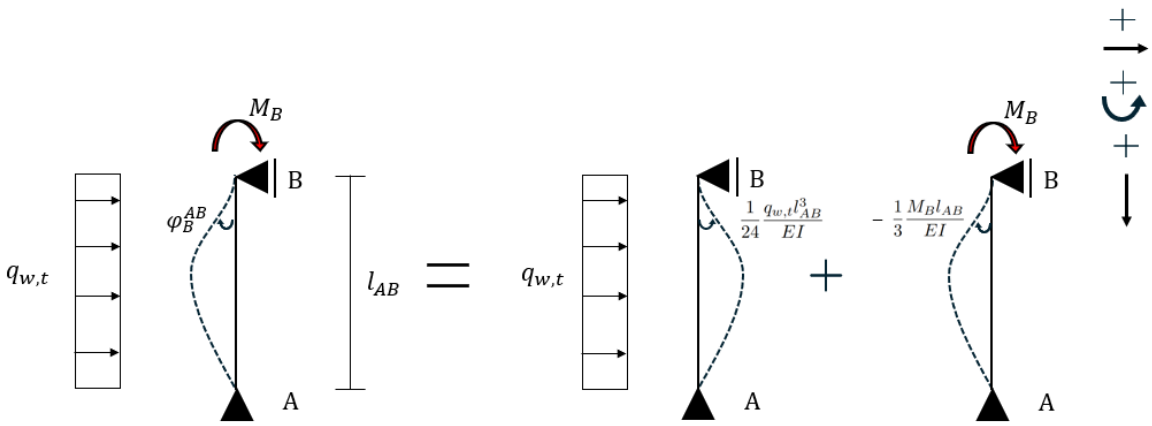

Figure 13: 'Hoekmethode' AB

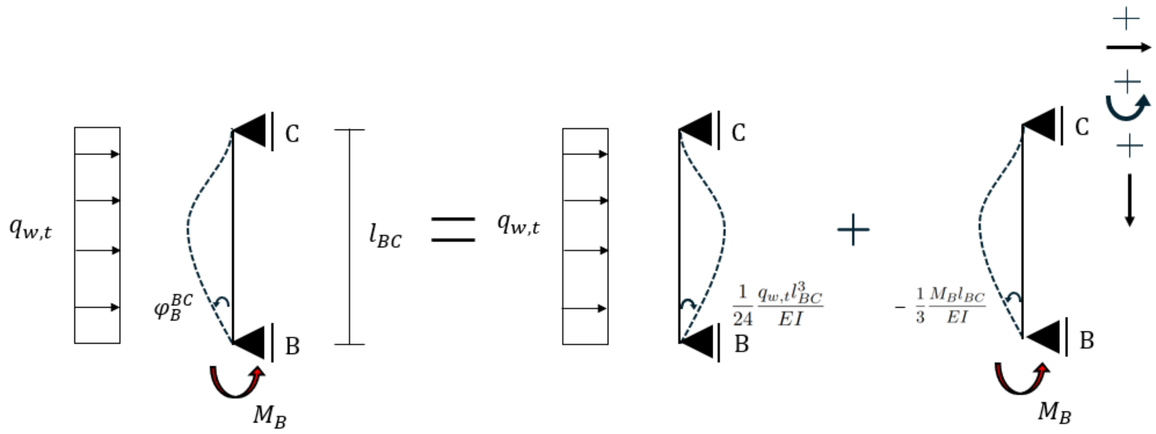

Figure 14: 'Hoekmethode' BC

$$
\begin{aligned}
\phi_B^{BC} &= \phi_B^{AB} \\
\frac{1}{24}\frac{q_{w,t}l_{BC}^3}{EI} - \frac{1}{3}\frac{M_B l_{BC}}{EI} &= \frac{1}{24}\frac{q_{w,t}l_{AB}^3}{EI} - \frac{1}{3}\frac{M_B l_{AB}}{EI} \\
M_B(l_{AB} + l_{BC}) \cdot 24EI &= (q_{w,t}l_{BC}^3 + q_{w,t}l_{AB}^3) \cdot 3EI \\
M_B &= \frac{1}{8}q_{w,t}(l_{BC}^2 + l_{AB}^2)
\end{aligned} \tag{21}
$$

$$
\begin{aligned}
M_{AB} &= \frac{M_B}{2} - \frac{1}{8}q_{w,t}l_{AB}^2 \\
M_{BC} &= \frac{M_B}{2} - \frac{1}{8}q_{w,t}l_{BC}^2
\end{aligned} \tag{22}
$$

Where:

$$
\begin{aligned}
\phi &= \text{Angular displacement [rad]} \\
q_w &= \text{Wind load per unit length [kN/m]} \\
l &= \text{Length [m]} \\
E &= \text{Young's modulus [N/m}^2\text{]} \\
I &= \text{Moment of inertia [m}^4\text{]} \\
M &= \text{Moment [kNm]}
\end{aligned}
$$

In total, this results in the moment diagram for the tower as shown in Figure 15.

The results of the tower calculations are shown in Table 3.

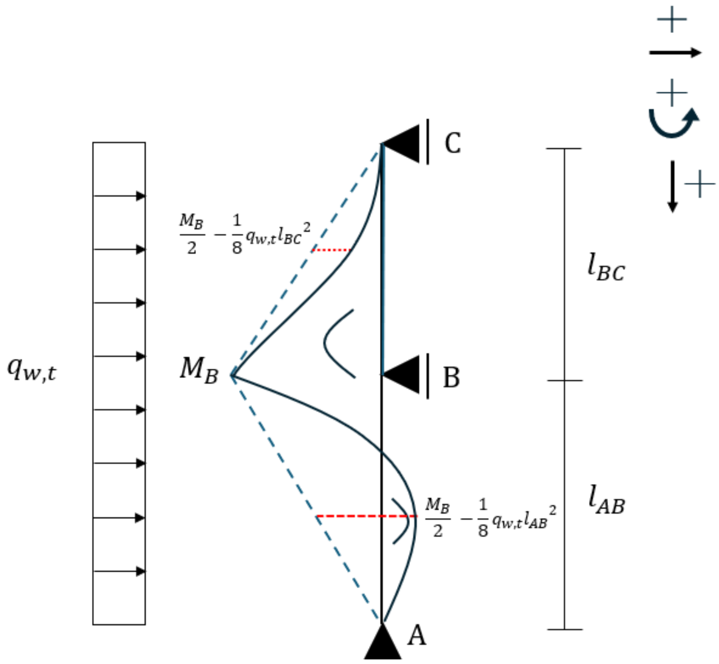

Figure 15: Moment diagram tower

Parameter	**Value**	**Unit**
H_C	2.6448	kN
H_B	2.2547	kN
H_A	1.0021	kN
V_C	5.6179	kN
V_B	2.4568	kN
V_A	17.2935	kN
$F_{\text{wire},1}$	6.2093	kN
$F_{\text{wire},2}$	2.6448	kN
$F_{\text{wire},4}$	3.3346	kN
M_B	3.8517	kNm
M_{AB}	0.4227	kNm
M_{BC}	-0.4227	kNm

Table 3: Structural calculations tower

5.4.4 Tension wires calculations

Pole guy wires to the ground

For the calculation of the guy wires, it is important to look for the worst-case scenario. In the case of the pole, the largest tension forces in the guy wires occur when the wind is aligned with one of the wires. The whole wind load will then be taken up by one guy wire. This is also represented in Figure 16. The resulting forces can be found in Figure 6.

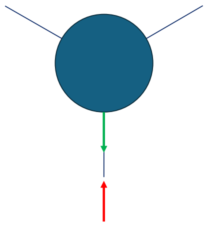

Figure 16: Pole tension force

$$F_{wire,2} = H_C$$
$$F_{wire,3} = \frac{H_D}{cos(\theta)}$$

Tower guy wires to the ground

To determine the tension in the guy wires anchoring the tower to the ground, the critical loading scenario must also be considered. Two scenarios are evaluated, one where the wind is aligned with one guy wire, as represented in Figure 17. And one where the wind acts perpendicular to the tower, where two guy wires will resist the force, as shown in Figure 18.

$$F_{wire,1} = \frac{H_C}{cos(\theta)}$$
$$F_{wire,4} = \frac{H_B}{cos(\theta)}$$

The dominant load will be when the wind is aligned with one guy wire, the whole tension force is then transferred to this one wire. The wind force in this case also acts on a larger area, since the load will be perpendicular to the diagonal of the tower. The resulting forces can be found in Figure 11.

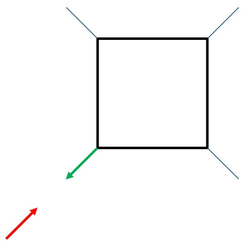

Figure 17: Force distribution 1

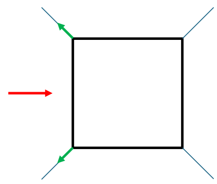

Figure 18: Force distribution 2

Guy wires along the tower

The bending moment acting on the scaffolding tower induces tensile forces in the vertical members on one side of the structure. However, the connections between the scaffolding elements are not designed to resist tensile forces. To ensure structural stability, guy wires need to be installed along all four sides of the tower. These wires take over the tensile forces when necessary and must therefore be capable of resisting the maximum force resulting from the moment. As shown in the moment diagram in Figure 15, the maximum moment occurs at point M_B, which induces tensile forces in two of the vertical poles. The maximum tensile force is calculated in Formulas 23. Here, F_{tension} represents the tensile force that each individual wire must be designed to resist.

$$\text{arm}_{\text{tower}} = \frac{\text{B}_{\text{tower}}}{2} \qquad (23)$$
$$F_{\text{tension}} = \frac{\frac{M_B}{2}}{\text{arm}_{\text{tower}}}$$

Since the scaffolding connections alone cannot reliably resist these tensile forces, the additional guy wires are responsible for transferring these loads safely. The forces resulting from the moment, as calculated in Formulas 23, are illustrated in Figure 19.

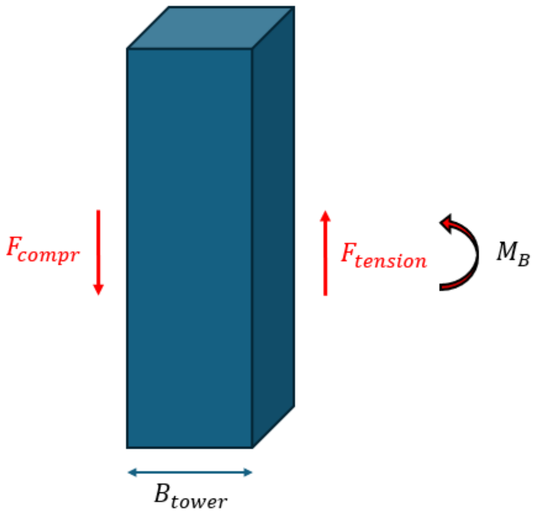

Figure 19: Tension force on tower

Dimensions guy wires
With all the loads on the tower and the pole calculated, the required dimensions of the guy wires can be determined. In the previous paragraphs, the loads from the pole and the tower that are transferred to the guy wires have been calculated. To obtain the total force in each wire, the wind load acting directly on the wires themselves is also taken into account, denoted as $q_{\text{wind,wires}}$. In Formulas 24, the subscript x refers to the four individual guy wires located on the sides of the tower, with $x = 1, 2, 3, 4$.

$$\begin{aligned} F_{\text{wire},x,\text{total}} &= F_{\text{wire},x} + (q_{\text{wind,wires}} \cdot l_{\text{wire},x}) \\ F_{designload} &= \frac{F_{breakload}}{\gamma_m} \\ \frac{F_{\text{wire},x,\text{total}}}{F_{designload}} &\leq 1 \end{aligned} \tag{24}$$

Where:

$F_{\text{break load}}$ = Break load of chosen guy wire [kN]
γ_m = Safety factor [−]

For the choice of the guy wires, contact was made with a local hardware store. The store provided information on wire diameters, break loads and other specifications that were used for dimensioning.

The results of the tension wire calculations are shown in Table 4.

Parameter	Value	Unit
$F_{\text{wire,1,total}}$	6.6183	kN
$F_{\text{wire,2,total}}$	2.6698	kN
$F_{\text{wire,3,total}}$	1.9753	kN
$F_{\text{wire,4,total}}$	3.5922	kN
$F_{\text{breakload}}$	29.5	kN

Table 4: Tension wires calculations

5.4.5 Foundation calculations

The tower and pole are being constructed on a site with ground conditions consisting of 60 cm of medium clay, followed by a 40 cm layer of medium clay mixed with gravel, and underlain by limestone. The exact location of the water table is unknown, but it is likely not at 1 meter below ground level, although it may rise during periods of heavy rainfall.

The structural loads of the pole are supported by a foundation pile under the pole, carrying a vertical load of $V_{A,p}$, as shown in Figure 6. Three pole guy wires anchored to three separate foundation points each carry a vertical load of V_D. Four foundation piles support the structural loads of the tower, each carrying a vertical load of $V_{A,t}$, as shown in Figure 11. Additionally, four guy wires, anchored to four separate foundation points, each carry a vertical load of $V_B + V_C$, supporting the tower's stability. In the calculations in this paragraph, the loads on the foundation piles under the guy wires are referred to as V_{gw}. The loads on the foundation piles under the pole and under the tower are referred to as $V_{p/t}$.

Foundation piles under guy wires
Figure 20 illustrates the foundation piles beneath the guy wires. At the centre of the foundation, a bar is bent and anchored to serve as a grounded connection point for the guy wires. This design was developed in collaboration with the CCFC staff, based on their experience with local construction practices.

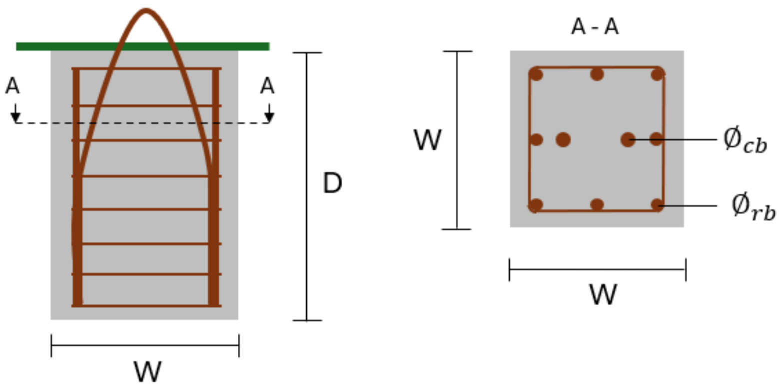

Figure 20: Sketch foundation pile under guy wires

The depth of the foundation piles is determined to be 1 meter, as this is the point where the foundation reaches the stone layer, which is favourable for stability. The foundation piles must be designed to resist the pulling forces from the guy wires, ensuring they do not become displaced or pulled out of the ground. The total force resisting the foundation's displacement is the sum of the dead weight of the foundation and the shear strength of the soil working on the side areas of the foundation. It is assumed that the passive ground pressure is zero, as the foundation is located on a ridge where the soil's ability to resist horizontal displacement is minimal. This resisting force must exceed the vertical loads that are applied to the pole guy wire foundations and tower guy wire foundations. By assuming a foundation width, the calculations shown in Formulas 25 should be iterated until this condition is met, with an assumed Factor of Safety of 3 taken into account.

The undrained shear strength parameter of a soil must be used in undrained analysis of piles (Wrana 2015). The undrained shear strength of medium clay is estimated to be 30 kPa (Xu et al. 2018), with a friction factor of 0.82 used to account for the adhesion between the clay and the foundation surface (Terzaghi et al. 1996).

$$\begin{aligned} F_r &= \frac{F_{d,f} + F_s}{FoS} \\ F_{d,f} &= V_f \cdot \rho_c \cdot FoS_{d,p} \\ F_s &= \alpha \cdot c_u \cdot A_{f,t,s} \\ V_f &= W \cdot W \cdot D \\ A_{f,t,s} &= 4 \cdot W \cdot D \\ V_{gw} &< F_r \end{aligned} \tag{25}$$

Where:

F_r = Resistance force [kN]
$F_{d,f}$ = Dead load foundation [kN]
FoS = Factor of safety [−]
V_f = Foundation volume [m^3]
ρ_c = Concrete density [kN/m^3]
$FoS_{d,p}$ = Factor of safety dead load working positive [−]
F_s = Shear resistance [kN]
α = Cohesion factor [−]
c_u = Undrained shear strength [kPa]
$A_{f,t,s}$ = Foundation total side area [m^2]
W = Width [m]
D = Depth [m]
V_{gw} = Applied vertical load on guy wire foundation pile [kN]

These foundation piles are subjected to tension from the guy wires, which is taken up by eight reinforcement bars, as shown in Figure 20. The total steel yield strength of 275 MPa, with a material Factor of Safety of 1.5 applied (Soons and van Raaij 2014), should exceed the applied tension, which is calculated by dividing the applied load by the total area of the eight reinforcement bars. By assuming a reinforcement bar diameter, the calculations shown in Formulas 26 should be iterated until this condition is met.

$$\begin{aligned} f_{yd} &= \frac{f_{yk}}{y_m} \\ \sigma_{rb} &= \frac{V_{gw}}{8 \cdot \pi \cdot \frac{D_{rb}^2}{4}} \\ \sigma_{rb} &< f_{yd} \end{aligned} \tag{26}$$

Where:

f_{yd} = Design yield strength [kPa]
f_{yk} = Characteristic yield strength [kPa]
y_m = Material factor [−]
σ_{rb} = Stress in the reinforcement bars due to tension load [kPa]
V_{gw} = Applied vertical load [kN]
D_{rb} = Reinforcement bar diameter [m]

A central bar is bent in the foundation piles to serve as the attachment point for the guy wires, as shown in Figure 20. The bent portion extends above the concrete, while the straight part is secured to the reinforcement bars at the bottom of the foundation using iron wire. It is necessary to check whether this bent central bar can withstand the tension exerted by the guy wires. The yield strength of the central bar is 275 MPa, with a material Factor of Safety of 1.5 applied (Soons and van Raaij 2014). Due to the bending of the bar, its effective yield strength is reduced. To account for this uncertainty, a conservative bending reduction factor of 0.5 is taken into account. This reduced yield strength should exceed the applied tension, which is calculated by dividing the applied load by the area of the central bar. By assuming a central bar diameter, the calculations shown in Formulas 27 should be iterated until this condition is met.

$$
\begin{aligned}
f_{yd,eff} &= \psi_b \cdot \frac{f_{yk}}{y_m} \\
\sigma_{cb} &= \frac{V_{gw}}{\pi \cdot \frac{D_{cb}^2}{4}} \\
\sigma_{cb} &< f_{yd,eff}
\end{aligned}
\tag{27}
$$

Where:

$f_{yd,eff}$ = Design yield strength [kPa]
ψ_b = Bending reduction factor [−]
f_{yk} = Characteristic yield strength [kPa]
y_m = Material factor [−]
σ_{rb} = Stress in the central bar due to tension load [kPa]
V_{gw} = Applied vertical load [kN]
D_{rb} = Reinforcement bar diameter [m]

Foundation piles under pole and tower
Figure 21 illustrates the foundation piles beneath the pole and tower. At the centre of the foundation, a central bar is placed to facilitate the sliding of the hollow piles of the pole and tower over it.

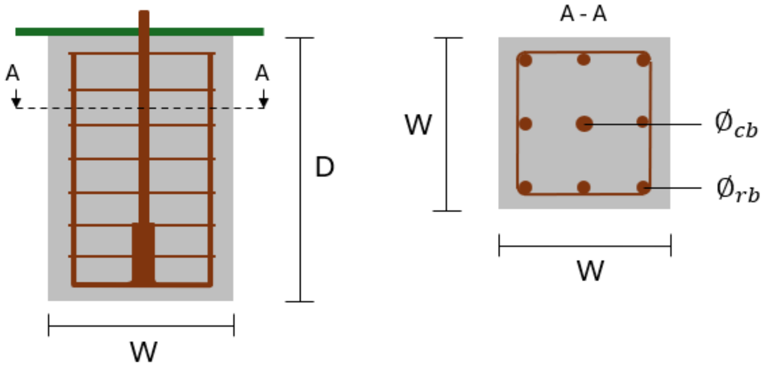

Figure 21: Sketch foundation pile under pole and tower

The depth of the foundation piles is determined to be 1 meter, as this is the point where the foundation reaches the stone layer, which is favourable for stability. Limestone has a shear strength of 10 MPa, with a material Factor of Safety of 1.5 applied (Soons and van Raaij 2014). This results in the allowable pressure on the stone. The applied pressure on the stone can then be calculated by assuming a foundation area and the applied load from the pole and tower. The applied pressure should be smaller than the allowable pressure, allowing the foundation area to be iterated accordingly, as shown in Formulas 28.

$$\begin{aligned} q_{all} &= \frac{q_f}{y_m} \\ q_{app} &= \frac{V_a}{W \cdot W} \\ q_{app} &< q_{all} \end{aligned} \tag{28}$$

Where:

q_{all} = Allowable pressure [kPa]
q_f = Shear strength [kPa]
y_m = Material factor [−]
q_{app} = Applied pressure [kPa]
V = Applied vertical load [kN]
W = Foundation width [m]

These foundation piles are subjected to pressure from the pole and tower, which is transferred through the concrete. It has to be checked whether the concrete can withstand this pressure. The characteristic compressive strength of the concrete is assumed to be 15 MPa, with again a material Factor of Safety of 1.5 applied (Soons and van Raaij 2014). The stress in the concrete, which is the applied force from the pole and tower divided by the assumed area, should be smaller than the design compressive strength, as shown in Formulas 29. If this condition is not met, the calculations in Formulas 28 and 29 should be iterated until both conditions are fulfilled.

$$f_{cd} = \frac{f_{ck}}{y_m} \tag{29}$$
$$\sigma_f = \frac{V_a}{W \cdot W}$$
$$\sigma_f < f_{cd}$$

Where:

f_{cd} = Design compressive strength [kPa]
f_{ck} = Characteristic compressive strength [kPa]
y_m = Material factor [−]
σ_f = Stress in foundation due to pressure load [kPa]
V_A = Applied vertical load [kN]
W = Foundation width [m]

For practicality, the same diameter is used for the reinforcement bars in the foundation piles under the pole and tower as those used for the guy wires. This assumption is made to standardise the reinforcement throughout the foundation piles, simplifying the construction process. The foundation piles under the guy wires are subjected to tension, while those under the pole and tower experience pressure. Since tension is the critical factor for the reinforcement bars, they are also sufficient to withstand the pressure forces.

No additional calculations are required for the central bar, as its diameter should match the inner diameter of both the pole (for the foundation under the pole) and the tower (for the foundation under the tower). This ensures proper fit. To stabilise the central bar, the bottom of the reinforcement bars is bent and securely fastened along the pole using iron wire, as shown in Figure 21.

The results of the foundation calculations are shown in Table 5.

5.4.6 Lightning protection system

A grounding system is integrated into the tower design. A copper wire is tightly attached along the full height of the tower, acting as the highest point to attract and safely guide lightning strikes. This wire is connected to a metal rod, driven at least 0.5 meters vertically into the ground to ensure proper discharge. Additionally, the electronic components, including sensors, data loggers and solar panels, are not directly connected to the tower's structure. By keeping the electronics isolated from the tower, a floating, self-contained system is created, reducing the risk of electrical damage in the event of a lightning strike.

5.5 Construction process

The construction process started with sanding and painting the scaffolding to make it more resistant to corrosion, as shown in Figure 22. After the design was developed in close collaboration with the CCFC team and local builders, the construction plan was revisited with them to prepare for implementation. These builders, employed by CCFC, possess practical experience and deep knowledge of local construction practices. Their Indigenous expertise, combined with the ecological and logistical understanding of the CCFC staff, proved essential to translating the design into the physical structure. Communication with the local builders, who primarily speak Q'eqchi' instead of Spanish, was facilitated by the CCFC team, who acted as interpreters

Foundation piles under pole guy wires		
Parameter	**Value**	**Unit**
W	0.30	m
D_{rb}	0.0127	m
D_{cb}	0.0191	m
F_r	10.4880	kN
V_{gw}	1.1092	kN
f_{yd}	183333	kPa
σ_{rb}	1095	kPa
$f_{yd,eff}$	91667	kPa
σ_{cb}	3892	kPa

Foundation piles under tower guy wires		
Parameter	**Value**	**Unit**
W	0.40	m
D_{rb}	0.0127	m
D_{cb}	0.0191	m
F_r	14.2720	kN
V_{gw}	8.0747	kN
f_{yd}	183333	kPa
σ_{rb}	7968	kPa
$f_{yd,eff}$	91667	kPa
σ_{cb}	28330	kPa

Foundation piles under pole		
Parameter	**Value**	**Unit**
W	0.30	m
D_{rb}	0.0127	m
D_{cb}	0.09	m
q_{all}	6667	kPa
q_{app}	109	kPa
f_{cd}	10000	kPa
σ_f	109	kPa

Foundation piles under tower		
Parameter	**Value**	**Unit**
W	0.30	m
D_{rb}	0.0127	m
D_{cb}	0.0337	m
q_{all}	6667	kPa
q_{app}	192	kPa
f_{cd}	10000	kPa
σ_f	192	kPa

Table 5: Foundation calculations

and advisors throughout the process.

Before building the structure, the construction site was levelled by the local team. Foundation pits were excavated for the tower feet and guy wire anchors. Reinforcement bars were tied and placed according to the design drawings, and concrete was mixed and poured on-site, as shown in Figure 23. The foundations were allowed to cure for three days to ensure sufficient strength.

After the curing period, the scaffolding tower was assembled layer by layer. The first level was already firmly fixed into the concrete base. After building the fourth layer of scaffolding, guy wires were attached to anchor the tower against wind forces. Once the first guy wires were tensioned to the correct tightness, the remaining five levels were installed. Upon reaching the final height, the second set of guy wires was anchored. These guy wires were tensioned manually, with local expertise ensuring that the correct tightness was achieved. Lastly, the vertical guy wires were installed along the side of the tower.

Finally, the lightning protection system and the measurement set-up were installed by this team, Cloud Chasers IV. A safety protocol was developed before this final step to protect both the team and sensitive equipment, and can be found in Appendix C.

5.6 Discussion

During the tower design and construction process, several insights emerged that extended beyond the technical aspects alone. These also included considerations for long-term monitoring, collaboration with local stakeholders and the challenges of working in remote environments.

Figure 22: Sanding and painting the scaffolding (Cloud Chasers IV, 2025)

Figure 23: Pouring the concrete (Cloud Chasers IV, 2025)

Planning underestimated

One of the main reflections is that both the design and construction phases took significantly longer than expected. Structural calculations required more iterations than anticipated, especially due to the need to verify, for example, stresses, deflections and buckling. The construction itself also took longer, in part due to communication challenges, but also because of the detailed work involved in aligning and securing scaffolding, guy wires and pouring foundations in difficult terrain. Future groups should be realistic about the time investment needed and include larger buffers for design refinement, materials sourcing and assembly. While the work was ultimately completed successfully, much of it required day-to-day problem-solving and flexibility that cannot be captured in static planning documents.

Different perspectives on safety

Working with a multicultural team also revealed different perspectives on safety. The design team initially approached safety from a Eurocentric engineering standpoint, focusing on risk assessments and predefined safety protocols. In contrast, the local team approached safety more pragmatically: to get something done, you make it work as safely as possible with the tools and experience you have. These two perspectives are not incompatible, but require negotiation. In practice, it meant that the team had to find a balance between formalised procedures (e.g., developing a safety plan for sensor installation at height) and local practices based on experience and situational awareness. This learning curve was an important part of building mutual respect and shared responsibility.

Involvement of local builders and CCFC staff

A strength of the process was the close collaboration with CCFC staff and local builders. The tower could not have been constructed without their active involvement. However, this collaboration also required careful communication and expectation management. Most of the builders spoke Q'eqchi' as their first language, which made Spanish communication difficult. Misunderstandings did not necessarily lead to critical mistakes, but they slowed down the planning and execution. For example, while preparing tasks from the base camp, it was not always possible to immediately communicate clarifications or changes once the team reached the construction site, 45 minutes away. This highlights the need for well-prepared, clearly illustrated and sequenced construction plans.

Balancing technical optimisation with environmental and cultural context
One of the challenges was balancing structural safety with ecological and cultural sensitivity. While the selected site successfully meets both in-canopy measurement needs and environmental constraints, achieving this balance required careful trade-offs and decision-making. Input from CCFC staff and local builders was essential in navigating spatial limitations, anchoring strategies and conservation concerns. At times, this led to tensions: CCFC, understandably committed to minimising ecological disturbance, expressed reservations about vegetation removal and soil modification required for the tower. These differences in priorities led to discussions on design decisions, ultimately resulting in a layout that all parties could support. This experience underscores that co-design is not merely beneficial but necessary in remote, ecologically sensitive contexts. It demands flexibility and consistent communication about design choices.

Structural design trade-offs and long-term flexibility
The decision to construct a 13.5-meter scaffolding tower, dimensioned for future extension to 25 meters, represents a strategic compromise. While the current set-up only facilitates in-canopy measurements, the structural calculations, material choices and foundation layout are all based on the full 25-meter design. This ensures that future upgrades can be implemented easily. However, this compatibility introduces trade-offs, including oversized components relative to their immediate loading conditions and higher up-front material and nature impact. These trade-offs were considered acceptable due to the long-term research horizon and the cost of future access and redesign in this remote environment. The approach reflects a design philosophy that prioritises modularity and resilience over short-term efficiency.

Limitations and assumptions in design and calculations
Several assumptions were required in the structural and foundation design due to practical constraints. Soil properties were inferred from qualitative inspection and typical values for similar conditions, as precise geotechnical surveys were not feasible. Conservative values were used for undrained shear strength and safety factors to ensure robustness, but this introduces inefficiencies in material use. Similarly, wind loading was based on Eurocode guidelines and local climate maps, but actual wind conditions in the cloud forest may vary. These limitations highlight the need for ongoing monitoring of structural performance and environmental loads, which can inform future design iterations and calibration of assumptions.

The role of standardisation and local adaptation
A feature of the tower design was the balance between standardisation (e.g., reinforcement bars, foundation depths) and local adaptation (e.g., anchoring methods, available materials), allowing the design to be both structurally sound and practical to implement. However, a recurring challenge was the tension between precise dimensioning and the realities of local availability, what was calculated was not always what could be sourced. This required a flexible approach, where calculations guided the design, but informed adaptations were made on-site.

Construction process: learning through iteration
Although the design was finalised before construction, several aspects were revisited and adjusted during the building process. This iterative process improved the reliability of the final set-up, while also providing important feedback loops. However, this adaptive process required continuous and clear communication, which was not always easy. At times, the CCFC team

expressed concern over specific design choices, not realising that these had already been revised, leading to unnecessary stress and underscoring the importance of aligning updates with all involved parties in real-time.

Sustainability and transferability
The constructed tower is not just a static infrastructure but a platform for long-term hydrological monitoring. Its ability to support diverse sensors and future upgrades increases its scientific value. Moreover, the construction methods and documentation are transferable to similar sites within the region. However, the long-term success of the tower relies on consistent maintenance and institutional memory. This requires continued engagement with CCFC. Ensuring the tower remains functional for at least 15 years means embedding it within an organisational structure that can support its upkeep beyond individual projects.

Other recommendations for future work
Future Cloud Chasers teams and researchers working at the site are encouraged to:

- Construct the pole that is accounted for in this design, and to visit local hardware stores to identify available steel pipes. The pole is essential for elevating the above-canopy sensors beyond the 13.5-meter tower, enabling measurements that cannot be obtained from the scaffolding alone. The Excel calculation sheet developed for this project allows users to input the dimensions (inner and outer diameter) of different pipes and immediately verify whether they meet structural safety requirements.
- Long-term sustainability of the tower does not end with construction. A full maintenance plan has been developed as part of this project, in Chapter 8. It is recommended to follow this plan and improve it based on experiences and tower adjustments.
- One element not yet addressed in the current set-up is protection against unauthorised access. The tower itself is climbable, and no locks or signage are present to restrict access. This introduces risks of unintended damage or injury, especially if the site becomes better known in the future. Future teams may consider lightweight solutions such as signage, locking mechanisms for the lower ladder segments or even community outreach to increase awareness and stewardship.

5.7 Conclusion

The completed 13.5-meter scaffolding tower is an important step in the realisation of a long-term hydrological monitoring station. It is designed for in-canopy measurements and dimensioned to support a future extension to 25 meters for above-canopy measurements. Its structural calculations accounted for wind loads, deflection limits, buckling risks and material stresses under Eurocode guidelines, ensuring safety under the site's environmental conditions. The design balances engineering with local feasibility. Key components, including guy wire foundations, pole dimensions and reinforcement bar specifications, were calculated to withstand expected loads with factors of safety, while allowing for material availability constraints. Final tower images are shown in Figure 24 and 25.

On-site, construction was guided by structural plans, but remained adaptive to field realities. The sloped and uneven terrain made foundation placement and guy wire alignment challenging, requiring adjustments even after excavation had begun. Nonetheless, the collaborative construction process between the design team, CCFC staff and local builders proved essential. It resulted in a structure that was both structurally sound and contextually sensitive.

Importantly, the tower is not a static structure but a functional platform for future research. The calculations and design documentation, including a dimensioning Excel, are structured to enable future teams to build upon this work with minimal redesign effort. The completion of this infrastructure, therefore, not only supports current monitoring goals, but also lays the groundwork for sustainable, long-term environmental data collection in the cloud forest ecosystem.

Figure 24: Bottom view tower (Cloud Chasers IV, 2025)

Figure 25: Side view tower (Cloud Chasers IV, 2025)

6 Objective B: Hydrological set-up

6.1 Introduction

Researching the hydrology of cloud forests in the Mestela catchment is crucial for understanding broader water related issues in the Alta Verapaz region, such as flooding and water scarcity. A holistic view of the entire catchment is essential, as problems in one area can impact others, whether through changes in infiltration, runoff, or river discharge.

Therefore, the objective of this chapter is to develop a long-term hydrological monitoring set-up and a compatible model that enhances knowledge of the canopy water balance and hydrological cycle. Monitoring data collected from the tower is intended to feed into hydrological models that simulate water movement across the catchment. These models allow us to better understand how land use, including cloud forests, influences water availability over time and space, and to predict how environmental changes might affect both local and regional hydrology.

This chapter firstly presents literature on catchment hydrology and the role of cloud forests within the catchment, identifying the key hydrological processes within the canopy water balance. Then, it describes the experimental set-up that was implemented to monitor these processes at the research site. Subsequently, it explores how the data collected by this set-up can be used in hydrological models. It describes the catchment-wide modelling structure and its connection to modelling the cloud forest specifically. The last part of this chapter focuses on the canopy water balance model that was created in this research, which uses the data collected by the monitoring set-up.

6.2 Literature: Hydrology of the Mestela river catchment and the role of cloud forests

Before diving into cloud forests, it is essential to obtain a better understanding of the overall hydrology of the catchment and its different land uses.

6.2.1 Catchment hydrology and hydrological connectivity

Catchments are closed hydrological systems where all processes are interconnected, as they contribute to the movement of water through a defined area. The interconnected nature of these processes reflects the Maya cosmovision, where the balance between water, land, and vegetation is seen as essential for harmony within the environment. Within the Mestela river catchment, this means that processes like precipitation, infiltration, runoff, and evaporation are not isolated events but are linked, influencing one another across time and space.

In the Mestela river catchment, a diversity of land uses further complicates its hydrological dynamics. It is composed of different land covers, such as agricultural areas, pine plantations, and forested lands, each with its own impact on water movement. The Mestela catchment is highly sensitive to changes in these land uses, as shown by the frequent occurrence of extreme hydrological events such as floods and droughts. In 2020, for example, an extreme flooding event resulted in a massive increase in streamflow. More recently in 2023, a prolonged rainy season led to substantial increases in streamflow, highlighting the region's vulnerability to water variability (Hiemstra 2024).

6.2.2 The role of cloud forests in the Mestela river catchment

Cloud forests are unique ecosystems that play a critical role in the hydrology of tropical montane regions like Alta Verapaz. These forests, found at higher elevations, are particularly well known for their ability to intercept fog, or horizontal precipitation, which occurs when clouds pass through the forest canopy and condense moisture on the vegetation. This process, which typically occurs between 840 and 3475 meters in Central America, provides a valuable water source, especially during dry periods when conventional rainfall is scarce. The efficiency of fog interception depends on several factors, such as canopy structure, leaf surface area, wind speed, and slope orientation (Holder 2005; LaBastille and Pool 1978).

The cloud forest canopy's ability to capture and store water results in increased base flow in streams and more stable water levels throughout the year. This moisture buffering helps reduce the extent of both flood peaks and drought induced low flows, making the cloud forest an essential component of the catchment's hydrological stability. These forests also act as natural filters, slowing down water movement and enhancing water quality by reducing soil erosion and sedimentation (Bruijnzeel 2004).

However, deforestation in the region has led to a decrease in cloud forest cover, which has significant hydrological consequences. Between 1986 and 2006, cloud forest cover in the Sierra Yalijux region decreased by 17.7%, primarily due to agricultural expansion, logging, and population growth. This loss of forest cover leads to reduced fog interception and consequently, lower base flow in rivers during the dry season. Furthermore, it disrupts the overall water balance, reducing the system's ability to attenuate flood peaks and causing increased streamflow variability (Hiemstra 2024).

6.2.3 Hydrological balance of the cloud forest canopy

Given the essential role of the cloud forest in regulating water flow through fog interception and moisture storage, it is critical to understand how it contributes to the overall hydrological balance of the canopy. Disturbances to the cloud forest, such as deforestation, directly affect its fog interception capacity, disrupting the natural regulation of water flow. As a result, the forest's ability to store and release water decreases, leading to heavier fluctuations in streamflow. Understanding these dynamics within the cloud forest canopy is essential for accurately modelling hydrological changes in the Mestela River catchment and for effective water resource management in the region.

The cloud forest canopy acts as the first interface between the atmosphere and the land surface, influencing how water enters, is stored, and exits the ecosystem. The quantification of these processes is important for assessing the broader hydrological dynamics of the cloud forest and its implications for the catchment. However, some of the processes are difficult to measure, such as evapotranspiration or horizontal precipitation (Ah-Peng et al. 2017). Hence, in this project a canopy water balance is used to determine the composition of the different hydrological processes within the assessed cloud forest.

In hydrological terms, the canopy's water balance consists of three main components: influx (the water entering the canopy), storage (the water held by the canopy), and outflux (the water leaving the canopy). These components interact with each other, affecting the amount of water available for the catchment and downstream ecosystems. A simplified overview of this is given in Figure 26.

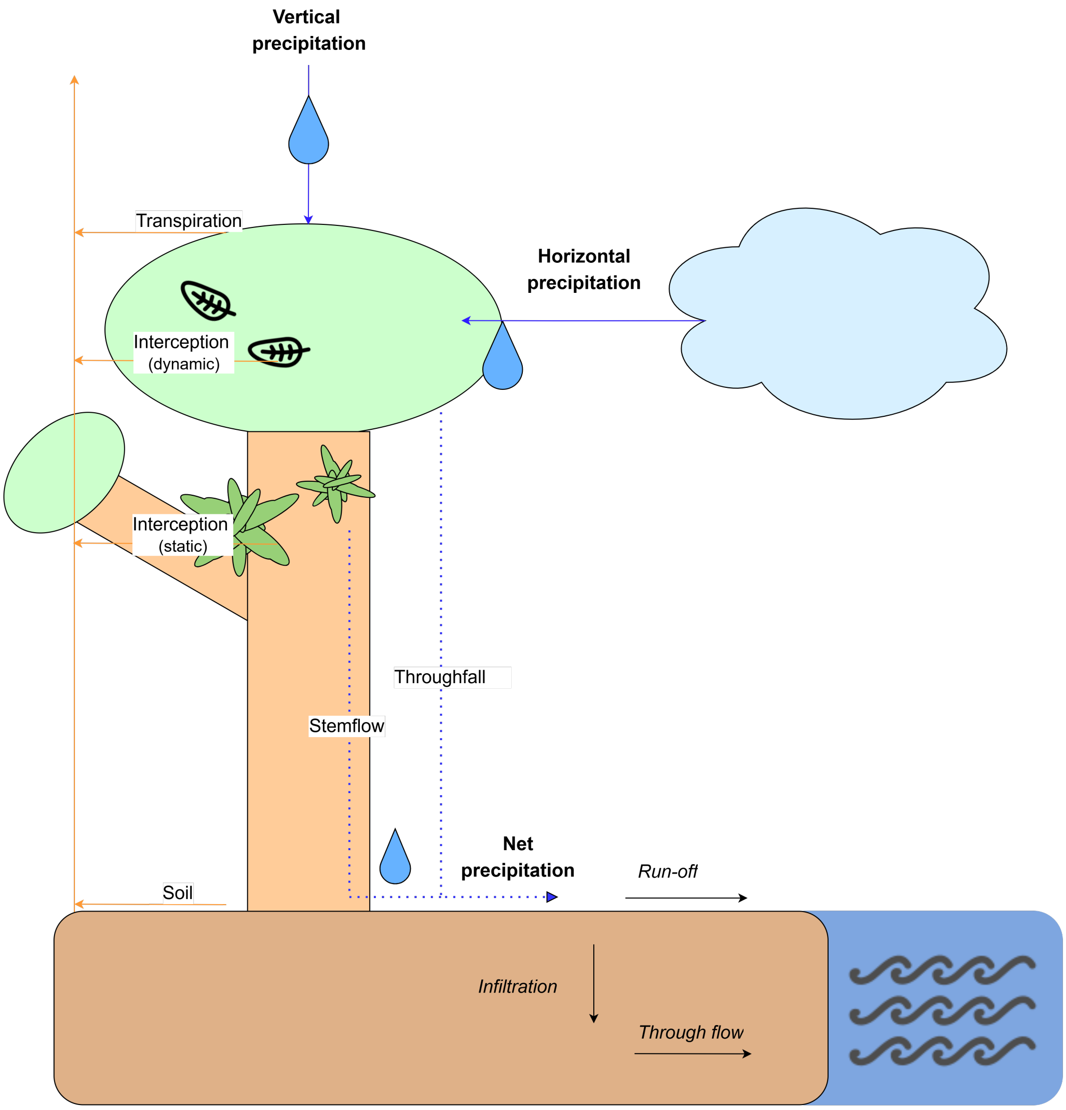

Figure 26: Simplified overview of the key hydrological processes within the canopy of a cloud forest

Influxes
The main water input in the canopy water balance is precipitation. Its characteristics vary depending on location, time, and climate. In the case of cloud forests, a distinction is made between:

- Vertical precipitation, or conventional rainfall, falls from above due to condensation in the atmosphere and is the most common form of precipitation.
- Horizontal precipitation, or fog interception, occurs when moisture in the form of fog or mist is carried horizontally by wind and intercepted by vegetation surfaces. While this form contributes relatively little in many environments, it is a significant water source in cloud forests due to frequent fog and clouds because of the forest's altitude and the large vegetation area within the dense forest (Bruijnzeel 2004).

Both forms of precipitation play important roles in the hydrological input of the system and should be considered when modelling the canopy water balance.

Storages
Before exiting the system, water can be temporarily stored in various places within the canopy. These storages buffer the flow of water through the system and influence how and when water becomes available downstream. Different storages retain the water for different periods of time, depending on the type of interception surface. The main types of storage in the canopy that are distinguished in this project are:

- Dynamic interception: When water is stored briefly on vegetation with low retention capacity (for example, vascular leaves) and released quickly, or moved to static interception storage (Cahill et al. 2023).
- Static interception: When water is held by components such as bromeliads, mosses, and canopy soil, which can store large quantities of water and release it slowly via evaporation or drainage (Cahill et al. 2023).

In cloud forests, epiphytes and dense vegetation can hold large amounts of intercepted moisture (Veneklaas et al. 1990). Especially non-vascular epiphytes could play a large role in cloud forest interception dynamics, since these organisms cover approximately 80-90% of the branches and vegetation in the research area (Boot et al. 2023; Veneklaas et al. 1990). Understanding this system of storages is an important part of understanding the water canopy balance.

Outfluxes
Water exits the canopy system through several outfluxes, which influence how water is distributed to the atmosphere, surface flow, and subsurface pathways. These include:

- Throughfall: Rain or intercepted water that drips or flows from leaves and branches to the forest floor. In cloud forests it often constitutes the majority of the precipitation that reaches the ground (Bruijnzeel 2001).
- Stemflow: Water that travels along branches and tree trunks before reaching the soil. Though typically a smaller component, it contributes to localised infiltration around tree bases.
- Evaporation and transpiration: These processes return water to the atmosphere. Evaporation occurs from wet surfaces, while transpiration happens when water taken up by plant roots is released through leaves.
- Infiltration and runoff: Once water reaches the forest floor, it either infiltrates into the soil or runs off along the surface, contributing to subsurface and groundwater flows. In principle, the forest floor within a cloud forest will not have much runoff since the infiltration capacity of the soil is high (Zimmermann et al. 2005).

Together, these outfluxes contribute to the regulation of water flow through the canopy and play a crucial role in the hydrological behaviour of the cloud forest, impacting streamflow and water availability for the larger catchment.

6.3 Experimental set-up

A hydrological monitoring set-up was designed to measure the meteorological conditions and components of the water balance of the cloud forest canopy that are explained in the previous sections. The set-up was installed in the constructed 13.5-meter scaffolding tower at the selected research site. As described in section 5, this tower is functional in the realisation of a long-term monitoring station. In this tower, different devices were installed for measurements and data collection. This section describes the central set-up devices, the combination of selected sensors, and how and where they have been installed.

6.3.1 Data logger and solar panel

The first central aspect of the monitoring set-up is the data logger (HOBO, RX3000), which transmits the collected data every 15 minutes. One data logger was available for this project, with a maximum amount of ten sensors. Hence, this was a boundary that had to be taken into account with the design of the set-up. To power the data logger, a 60 Watt solar panel was bought from a local store. A 60 Watt panel was selected, since the 5 Watt panel of the previous research group did not generate sufficient energy to power the data logger. Hence, a higher wattage should be able to power the data logger when there is less sun as well.

Figure 27: The installation at 13.5 meters, including the data logger (beige box) and solar panel

6.3.2 Canopy influx measurements

To measure the influx processes of the canopy water balance, different methods were employed to assess the vertical and horizontal precipitation.

Vertical precipitation
To quantify the vertical precipitation at the research site, a tipping bucket (Davis, S-RGF-M002) was installed in the top part of the tower (Figure 28) and connected to the data logger. This tipping bucket has a precision of 0.2 mm when it tips. It has been installed as high as possible at 13.5 meters, to have minimal shielding of surrounding trees.

Figure 28: The tipping bucket installed at 13.5 meter height, serving to monitor the vertical precipitation

Horizontal precipitation
Measuring how much water forest canopies capture from fog is difficult due to the variability in vegetation and conditions. Artificial fog gauges help track changes in fog over time but don't replicate how vegetation captures fog. In this study, homemade fog traps are used to observe fog patterns, though they don't quantify actual fog interception. A correction factor could in theory be used to compare gauge data to canopy capture, but there is not enough data available in this project to calculate this or estimate total fog flux.

The fog trap design of Cloud Chasers II Boot et al. 2023 was reused in this project. A cylindrical wire-harp fog trap, based on previous studies (Berrones et al. 2021, Ritter et al. 2015, Frumau et al. 2011, January), was used to capture horizontal precipitation, though some vertical precipitation may still influence results despite a roof shield designed to reduce it. The trap's open structure and the angle of rainfall allow vertical drops to enter. The trap is made of 0.5 mm nylon fishing line, vertically arranged with 2 mm spacing, wound around a saw blade to maintain uniformity. It is 46 cm tall, has a 20 cm diameter, and a 920 cm^2 collection area. The plastic cover spans 70 cm in diameter.

Two fog traps were installed at the top of the tower at 13.5 meters to minimise shielding from the tower itself and surrounding trees. The collected water from the fog traps is sent to a tipping bucket (Davis, S-RGF-M002) through a system of funnels, PVC pipes and hoses. The tipping bucket is connected to the data logger. See Figure 29 and Figure 30.

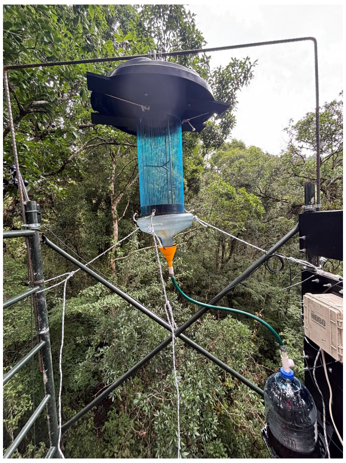

Figure 29: One of the two fogtraps installed at the top of the tower, including the connection to the tipping bucket which is in its turn connected to the data logger

Figure 30: The connection of the fogtrap to the hose leading the collected water to the tipping bucket. A combination of funnels was used

In addition to the fog traps, wind speed, relative humidity, and temperature sensors are used in the model to account for atmospheric conditions influencing fog deposition. Wind speed helps estimate the movement and intensity of fog, while relative humidity and temperature contribute to the potential for fog formation and its interaction with the canopy. More specifically, fog dynamics are influenced by the liquid water content (LWC) of the air, which depends on temperature and relative humidity. These sensors measure environmental conditions that help estimate the LWC, a key factor in fog formation. Wind speed, relative humidity, and temperature are integrated into the hydrological modelling structure to improve the estimation of evaporation and fog-related water fluxes.

6.3.3 Canopy storage measurements

The storage of water within the canopy is very difficult to directly measure, but can be estimated by using a model. This, therefore, means the canopy storage remains an estimation where the goal of the model is to obtain an accurate representation by calibrating several input parameters for the model. For this, other water flows are used to determine the best set-up to accurately represent these storages.

6.3.4 Canopy outflux measurements

To measure the different outflux processes, methods were employed to assess throughfall, evapotranspiration processes, and infiltration. Due to a lack of time and capacity for sensor connections to the data logger, no stemflow monitoring method has been installed.

Throughfall

To measure the throughfall in the study area, a set-up was created using three gutters, each 200 cm long and 10 cm wide. Together, these gutters cover a total area of 0.6 m^2 and are placed under the canopy to collect throughfall. An overview of the gutter placement in the study area is shown in Figure 31. Due to the uneven distribution of the tree canopy, the gutters are randomly positioned across the area to represent this uneven distribution. The gutters are connected by PVC pipes to a single tipping bucket (Davis, S-RGF-M002) at the bottom of the tower, which sends data to the data logger for monitoring. This is shown in Figure 32.

Figure 31: An overview of the three PVC gutters, randomly positioned, used for the throughfall set-up

Figure 32: The tipping bucket at the base of the tower, collecting the water from the throughfall set-up

To protect the throughfall set-up from accumulation of debris, chicken wire was placed on top of the gutters. The wire was installed all around the gutters, to prevent debris collecting in between the wire and the PVC. It could be argued that placing something on the collection gutters could interfere with the measurements. However, the work of the previous Cloud Chaser groups has shown that the throughfall set-up tends to be more sensitive to debris accumulation. Hence, it was considered that limiting this would outweigh the minimal interference of the wire on the measurements.

Another measure taken to minimise debris clogging the set-up, was the placement of filters between the gutters and their connected PVC elbows. These were not glued, to ensure that they could be taken apart and cleaned during regular maintenance.

Evapotranspiration processes

Measuring evapotranspiration processes is challenging. These processes are affected by both the physiological and morphological characteristics of the canopy, soil properties, and vegetation (Staudt et al. 2010). Additionally, meteorological factors, including wind speed, air temperature, humidity, and solar radiation, play a significant role in shaping the evapotranspiration process within and above the canopy. By monitoring these meteorological parameters and using them in hydrological models, both potential and actual evapotranspiration can be estimated.

Hence, the sensors relevant for monitoring evapotranspiration include two temperature/relative humidity sensors, two solar radiation sensors, and one wind speed sensor, all of which were installed as part of the set-up. To capture the spatial variation in environmental conditions at different canopy levels, two temperature/relative humidity (Onset, S-THC-M008) sensors were installed at two different heights: 13.5 meters and 2 meters above ground. At these same heights, two solar radiation sensors (Onset, S-LIB-M003) were installed. The 13.5-meter height corresponds to the upper canopy, which is crucial for understanding the atmospheric conditions and energy balance at the forest canopy level. The 2-meter height was chosen since this is the standard height for meteorological measurements. By placing the sensors at these two heights, the difference in evapotranspiration processes can be assessed between the canopy and the surface with the FIESTA model. Using a vertical gradient is important to enhance understanding of how water is transferred through different canopy layers and helps explain the roles of canopy structure, atmospheric conditions, and vegetation (Staudt et al. 2010). A wind speed and direction sensor (Onset, S-WCF-M003) was installed only at 13.5 meters.

Each of the sensors installed in the study area plays a specific role in providing the data required for accurate evapotranspiration modelling. Below is a detailed explanation of the key sensors and their functions:

- **Temperature Sensor:** Temperature is a critical factor influencing both the energy available for evapotranspiration and the rate of water vapour transfer. Air temperature is used to calculate the saturation vapour pressure, which is essential for determining the potential evaporation. Sensors were placed at both 2 meters and 13.5 meters to capture the temperature variation between the canopy and near-ground layers.
- **Relative Humidity Sensor:** Relative humidity is measured at both the 2 and 13.5 meter heights and can be used to calculate the vapour pressure deficit, which is the difference between the actual vapour pressure and the saturated vapour pressure. A large difference generally means higher evaporation rates, while a small difference implies less evaporation. These data are incorporated to estimate the atmospheric demand for evapotranspiration, with a direct influence on the potential and actual evapotranspiration calculations.
- **Wind Speed Sensor:** Wind speed is a critical factor in determining the aerodynamic resistance. Wind increases the movement of air over the vegetation, thereby influencing the rate of water evaporating from the canopy. Higher wind speeds reduce aerodynamic resistance, leading to increased evapotranspiration rates.
- **Solar Radiation Sensor:** Solar radiation is the primary source of energy for evapotranspiration. The energy from the sun is absorbed by the surface and vegetation, driving the evaporation process. Solar radiation is measured at both the 13.5-meter and 2-meter heights to assess the radiation intercepted by the canopy and near-surface layers. This measurement is used to estimate the available energy for evapotranspiration and is an essential input to determine the potential evapotranspiration.

Figure 33: The temperature/relative humidity sensor, installed at 13.5 meters (2 meter sensor not shown)

Figure 34: The wind speed and direction sensor, installed at 13.5 meters (only one sensor installed)

Figure 35: The solar sensor installed at 13.5 meters (2 meter sensor not shown), including attachment arm

The sensor data collected on temperature, relative humidity, wind speed, and solar radiation are used to quantify both potential and actual evapotranspiration processes in the study area. The potential evaporation can be calculated by using the Penman-Monteith equation, used by previous Cloud Chaser projects (Boot et al. 2023; Cahill et al. 2023). The Penman-Monteith equation, takes into account the available energy (solar radiation) and the atmospheric demand (vapour pressure deficit and wind speed). However, in this project cycle the FIESTA hydrological model was the main method for evaporation calculations. FIESTA (Fog Interception for the Enhancement of Streamflow in Tropical Areas) is a spatially distributed empirical model that estimates potential evaporation, wind driven precipitation, and fog interception in mountainous tropical regions. It adjusts coarse meteorological data using topography (elevation, slope, aspect) and land cover to simulate above ground hydrological processes. FIESTA integrates remote sensing, land surface properties, and simplified energy balance calculations to generate spatially distributed inputs for hydrological modeling, such as potential evapotranspiration and fog inputs. This will be explained in more detail in section 6.4.3.

For now, it is important to note that the temperature and relative humidity data are used to fit the measurements to a saturation vapour pressure curve. This curve is empirically computed. With the fitted slope of this curve and the solar radiation measurements, the potential evapotranspiration is calculated. This is then adjusted based on vegetation cover and other factors to estimate the actual evapotranspiration.

To quantify the actual evapotranspiration, a vegetation specific factor is applied to the potential evaporation, accounting for the vegetation type, canopy structure, and moisture availability in the study area. This adjustment ensures that the model reflects the actual conditions of the forest ecosystem.

$$ActEvap = \text{PotEvap\_adj} \cdot EtFrac_{total} \tag{30}$$

In this equation, the parameters are defined as follows:

- PotEvap_adj = is the adjusted potential evapotranspiration, calculated by dividing the potential evapotranspiration (PotEvap) by the latent heat of vaporization.
- $EtFrac_{total}$ = A dimensionless, dynamically modelled factor that scales potential evapotranspiration to actual evapotranspiration. In FIESTA, it is derived from modelled evaporation at spatial and temporal scales and plotted against LAI, capturing the influence of vegetation type, canopy structure, soil moisture, and climate conditions.

Thus, by incorporating data from these sensors into the hydrological models, we can obtain estimates of evapotranspiration processes.

Infiltration
To be able to monitor soil infiltration, two different soil moisture sensors (Onset, S-SMD-M005) were placed at different soil depths. The first one is installed at 10 centimetres depth, the second one at 30 centimetres. Both sensors are placed at a 4-meter distance from the monitoring tower.

6.3.5 Overview of monitoring set-up

Table 6 summarises the different sensors used in the monitoring set-up, their placements, and the aspects of the hydrological canopy water balance they monitor.

Table 6: Overview of sensors, their placements, and the hydrological aspects they monitor.

Sensor Type	**Placement (Height/Location)**	**Hydrological Balance Aspect**	**Notes**
Data Logger	13.5 meters (Top of the tower)	General Data Collection	Collects and transmits data from all sensors every 15 minutes.
Solar Panel	12 meters (Near the top of the tower)	Evapotranspiration	Powers the data logger for continuous data collection.
Tipping Bucket	13.5 meters (Top of the tower)	Vertical Precipitation	Measures vertical precipitation (rainfall).
Tipping Bucket	13.5 meters (Top of the tower)	Horizontal Precipitation	Connected to fog traps for capturing horizontal precipitation.
Tipping Bucket	Ground Level (Below the tower)	Throughfall	Measures throughfall (water passing through the canopy).
Wind Speed Sensor	13.5 meters (Top of the tower)	Horizontal Precipitation, Evapotranspiration	Monitors wind speed to estimate fog deposition and aerodynamic resistance in evapotranspiration model.
Temp/RH Sensor	2 meters and 13.5 meters	Evapotranspiration, Horizontal Precipitation	Combined sensor for air temperature and relative humidity, used to calculate vapor pressure deficit for evapotranspiration and LWC for fog dynamics.
Solar Radiation Sensor	2 meters and 13.5 meters	Evapotranspiration	Measures solar radiation to estimate available energy for evapotranspiration.
Soil Moisture Sensors	10 cm and 30 cm depth (4 meters from tower)	Infiltration	Monitors soil moisture to estimate infiltration and soil water dynamics.

6.3.6 Attachment mechanisms and accessories

To mount the sensors and cables onto the monitoring tower, various attachment mechanisms were designed and implemented. To allow for quick installation of the data logger and sensors at the top of the tower, they were first secured to plastic sheets. These sheets were then efficiently fastened to the tower using metal clamps. Because each sensor has a different shape, size, and mounting requirement, and because different positions on the tower present different structural constraints, the plastic sheets were customised accordingly. In Appendix F and G, an overview is provided with pictures of the set-up for each sensor. This approach ensures that during maintenance the components can be easily removed, and it simplifies construction by avoiding the need to handle numerous screws and bolts at a height of 13.5 m.

To suspend the fog traps with minimal obstruction, they were mounted on bent rebar arms, which were firmly attached to the upper section of the tower using metal clamps.

For sensors installed at lower heights (ground level and 2 meters), extension cables were used to connect them to the data logger. These cables were routed through PVC pipes to protect them from rain and animal interference.

To protect the temperature/relative humidity sensors from the effects of the sun, solar shields were made and installed. Together with the women of the CCFC team, plastic bowls were assembled on pins, to create a structure in which the sensor could be placed. The shield protects from the sun, but ensures air flow for accurate measurements. More information on the making of the shields can be found in section 7.

To translate the observed water fluxes into catchment insights, a modelling framework is required. The next section presents this framework.

6.4 Modelling structure

As explained, a realistic modelling set-up requires a continuous connection between the overall catchment and the cloud forest canopy. This necessitates models that operate at multiple spatial scales. The first scale involves simulating the hydrology of the entire catchment, which means that the correct land use types must be assigned to the appropriate locations within the landscape. This is done by the FlexTopo framework, which determines the relevant land class based on spatial characteristics such as elevation, slope, and land use.

The FlexTopo model has been thoroughly described by previous Cloud Chasers groups. More information is available in Hiemstra 2024 and Boot et al. 2023. Unlike previous studies, this research focuses on modelling a single land use type, a cloud forest, using a simplified bucket model, calibrated with long-term field data collected at the constructed tower.

Given that the processes within a catchment are interconnected, two key principles are central to the model design. First, it is essential to define a consistent structure for inputs and outputs, which allows different land use types to be combined flexibly and integrated in an overall model. Second, each land use class must also be internally modular to allow for the implementation of land use-specific processes, such as fog interception in cloud forests or infiltration in agricultural areas.

To achieve this, the model is built using object-oriented programming, where a shared Base Land Class defines the general structure for land units. Each specific land use type (e.g., cloud forest, wetland, agriculture) inherits from this base class, implementing its own processes while following the same interface. This structure provides both consistency and adaptability, allowing land classes to be easily integrated or modified without disrupting the broader model framework.

A schematic overview of the catchment hydrology model, including its land use-specific components, is shown in Figure 37.

In addition, Figure 36 illustrates the modelling workflow, from FIESTA output and forcing data to the FlexTopo input and the different hydrological response units (HRUs). The figure also shows where this study is situated within the modelling chain, with the red box marking the focus of this study.

Earlier models developed by Cloud Chasers groups offered valuable insights but lacked modularity, making it difficult to adjust or add new land use types without rewriting large parts of the code. This research addresses that limitation by introducing a dedicated base class and specific land class for cloud forest ecosystems, which fits into a flexible, modular structure. This set-up not only allows for more accurate cloud forest modelling, but also gives the opportunity to, in

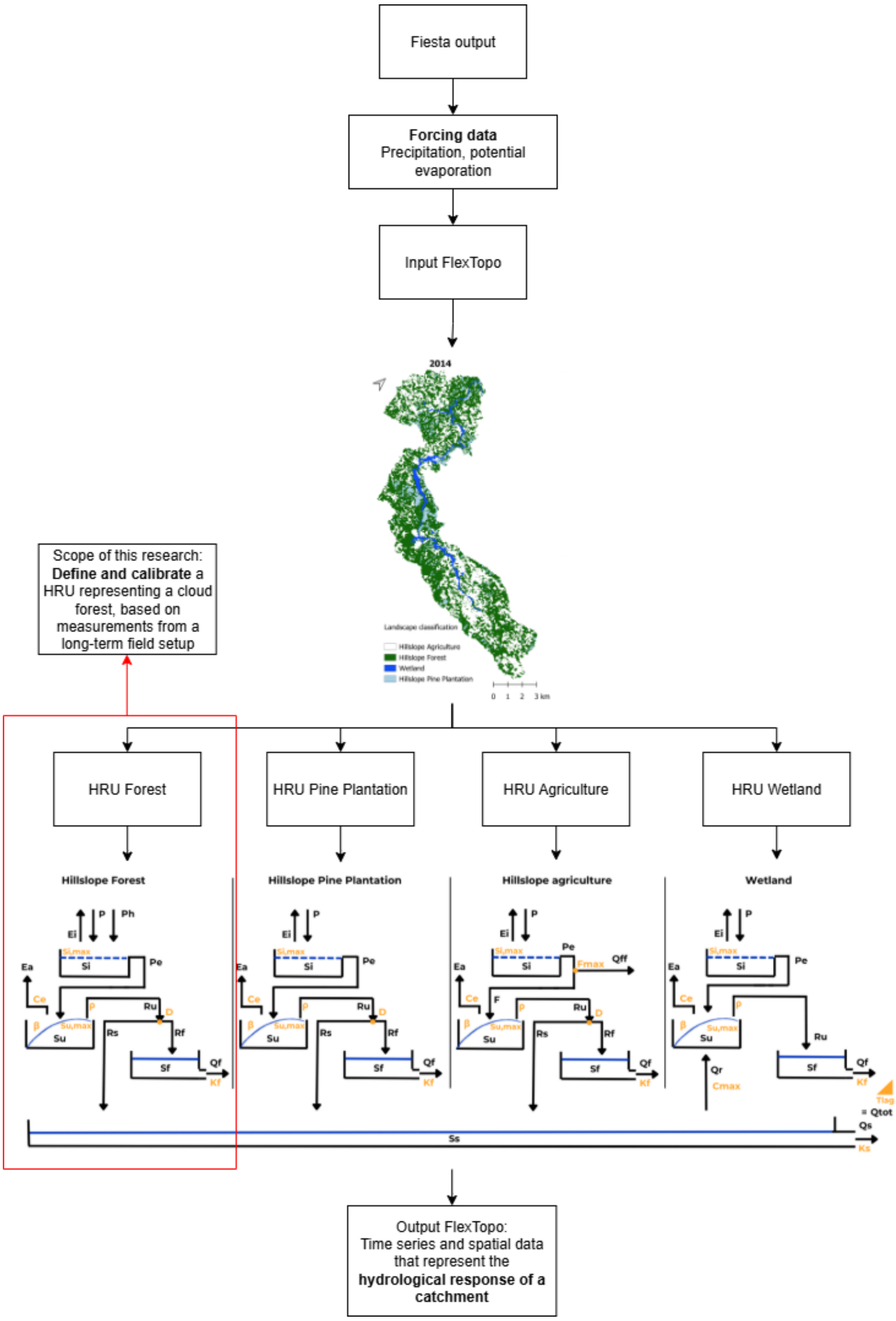

Figure 36: Schematic overview of the catchment hydrology model, showing land use-specific components. The red box highlights the scope of this research: defining and calibrating a cloud forest HRU

the future, add and change other land uses as needed without compromising similar outputs.

In this context, while the theoretical foundations developed by earlier groups remain valuable, reusing their code directly was not feasible due to the need for a more flexible, modular structure.

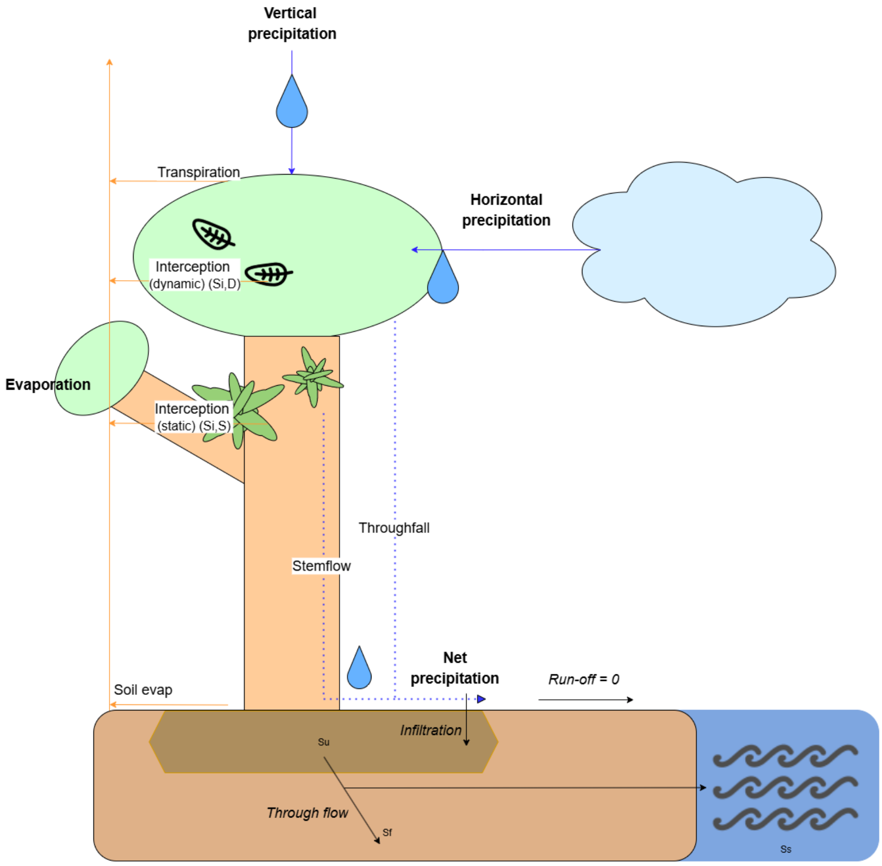

Figure 37: Overall catchment hydrological model

6.4.1 Creation of the Base Class

In the representation as seen in Figure 37, four key storage layers are identified as common across all land use types within the catchment as stated by Hiemstra 2024:

Si (Interception storage) [mm]: Rainfall captured and temporarily held by the vegetation
Su (Unsaturated zone storage) [mm]: Water stored in the unsaturated root-zone
Sf (Subsurface storage) [mm]: Water stored in the deeper subsurface, such as caves, karst systems, or other lower geological formations, below the root zone and main groundwater body
Ss (Slow storage) [mm]: Deeper groundwater storage contributing to groundwater flow

This schematic simplifies the complex spatial interactions into a modular flow diagram, showing how each land use type connects its internal storages (Si, Su, Sf, Ss) to the larger catchment hydrological processes through standardised pathways. By using this schematic structure, these storage layers can be treated as building blocks of the model, implemented across all land use types. This modularity ensures that each land use contributes to the overall catchment hydrology while allowing for internal flexibility and land use-specific processes within each storage layer. All land use types represent these processes consistently and contribute to the overall catchment hydrology. In this way, the Base Land Class is defined as a shared structure across all land use types. The Land Use classes can then define how each class simulates the processes within these storages, allowing for land use-specific behaviour while maintaining a consistent structure.

6.4.2 Cloud Forest Class

With the determined base class, the model for the hydrology of the cloud forest is determined. This can be divided into the four storage levels identified in the base class:

- **Si**, the interception storage: in the cloud forest water balance, this receives input from both vertical precipitation (rainfall) and horizontal precipitation (cloud or fog water). This dual input is what distinguishes cloud forests from other land classes.
- **Su**, the unsaturated storage in the soil.
- **Sf**, the fast-reacting reservoir.
- **Ss**, the slow-reacting reservoir, representing deep infiltration and groundwater flow.

Another distinction of a cloud forest is the combination of dynamic and static interception. Dynamic interception occurs when rainfall is temporarily captured on leaf surfaces, while static interception represents the absorption of cloud water by epiphytes, mosses, etc. This dual interception is characteristic of cloud forests and influences their water balance.

The interception storage Si in a cloud forest requires particular attention. It represents the canopy water storage, where vertical and horizontal precipitation inputs interact with the vegetation structure. To capture this process, a canopy water balance model was developed, as shown in Figure 38.

The model accounts for two primary inputs: vertical and horizontal precipitation. The interception process is divided into two interacting storages:

- **Dynamic interception storage (SI,D,max)**: the fast storage on leaf surfaces and branches. It is filled by both rainfall and cloud water. Once saturated, it drains quickly as throughfall, stemflow, drips into static interception, or evaporates back into the atmosphere.
- **Static interception storage (SI,S,max)**: this is slower storage, such as mosses and epiphytes. It is filled through drainage from the dynamic layer and loses water via slow dripping or evaporation.

Water that is not retained in the canopy becomes effective precipitation Peff, contributing to the soil moisture Su and, depending on the infiltration capacity and saturation, to the fast Sf or slow Ss reservoirs.

This canopy model ensures a physically accurate representation of interception in cloud forests by distinguishing between dynamic and static processes. Some input variables required by the model cannot be directly measured in the field, this is why a pre-processing step is required through the FIESTA framework. In the next section, more is explained about the FIESTA framework.

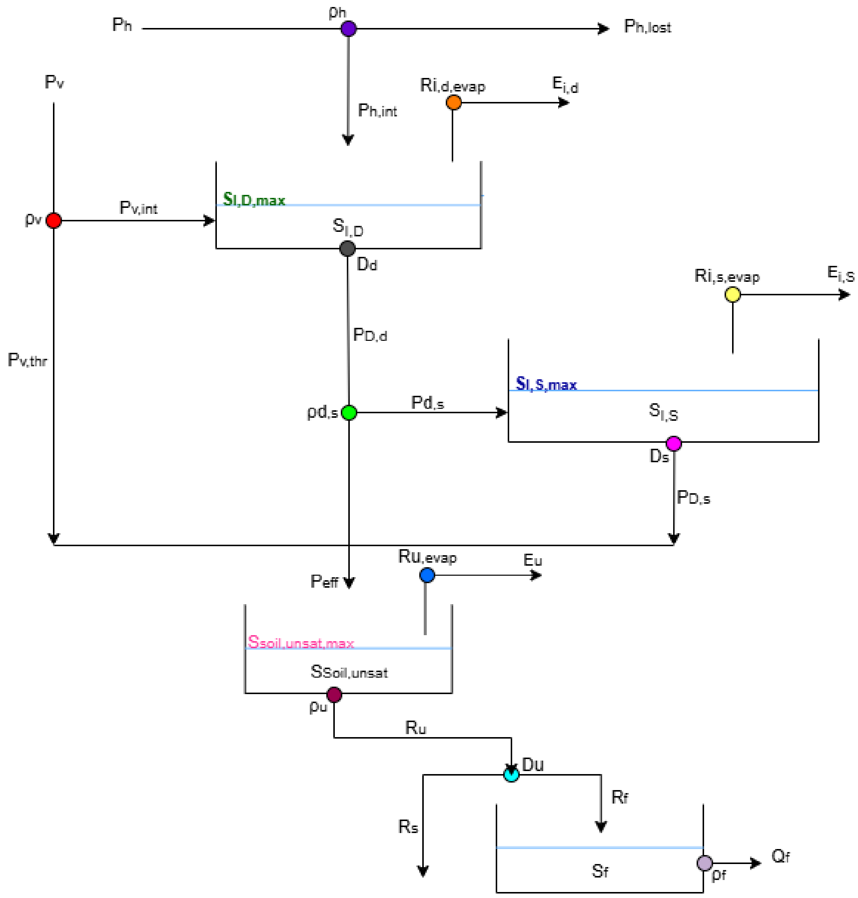

Figure 38: Canopy Water Balance

Where:

Parameters:

ρ_h = Fraction horizontal precipitation intercepted [-]

$R_{i,d,evap}$ = Evaporation rate from intercepted dynamic storage [mm/d]

ρ_v = Fraction vertical precipitation intercepted [-]

D_d = Dynamic storage drip coefficient [d^{-1}]

$\rho_{d,s}$ = Fraction dynamic storage drip intercepted by static storage [-]

D_s = Static storage drip coefficient [d^{-1}]

$R_{i,s,evap}$ = Evaporation rate from intercepted static storage [mm/d]

$R_{u,evap}$ = Evaporation rate from the unsaturated soil [mm/d]

ρ_u = Run-off coefficient from unsaturated soil [-]

D_u = Division parameter between fast- and slow-reacting run-off [-]

ρ_f = Outflow coefficient from fast-reacting reservoir [-]

Fluxes:

P_v = Vertical precipitation [mm/d]
$P_{v,int}$ = Intercepted vertical precipitation [mm/d]
$P_{v,thr}$ = Throughfall [mm/d]
P_h = Horizontal precipitation [mm/d]
$P_{h,int}$ = Intercepted horizontal precipitation [mm/d]
$P_{h,lost}$ = Lost horizontal precipitation [mm/d]
$E_{i,D}$ = Evaporation intercepted dynamic storage [mm/d]
$P_{D,d}$ = Drip from dynamic storage [mm/d]
$P_{d,s}$ = Drip from dynamic to static storage [mm/d]
$E_{i,s}$ = Evaporation from intercepted static storage [mm/d]
$P_{D,s}$ = Drip from static storage [mm/d]
E_u = Evaporation from unsaturated soil [mm/d]
R_u = Run-off from unsaturated soil [mm/d]
R_f = Fast-reacting run-off [mm/d]
R_s = Slow-reacting run-off [mm/d]
Q_f = Outflow from the fast-reacting reservoir [mm/d]

States:

$S_{i,D}$ = Intercepted dynamic storage [mm]
$S_{i,S}$ = Intercepted static storage [mm]
$S_{soil,unsat}$ = Unsaturated soil [mm]
S_f = Fast-reacting reservoir [mm]

6.4.3 FIESTA

The inputs of the canopy water balance model include horizontal precipitation (fog) and potential evaporation, which are difficult to measure directly and accurately in the field. Therefore, a pre-analysis step is required to estimate these values.

To do this, the FIESTA (Fog Interception and Evaluation System for Tropical Areas) framework is used. FIESTA provides empirical and physically based formulas developed specifically for subtropical montane cloud forest environments. These formulas enable the estimation of variables that are necessary for modelling the water balance. The framework combines empirical relationships with simplified physically based equations to estimate potential evaporation, fog interception, and wind driven precipitation.

Fog traps are used to detect when a fog event occurs. However, while the presence of fog can be identified, the quantity of intercepted fog is not reliably measurable with this method. Therefore, when a fog event is measured in the absence of rainfall, the FIESTA framework is applied to estimate the amount of horizontal precipitation.

FIESTA also accounts for spatial heterogeneity by incorporating topographic variables such as elevation, slope, and aspect, as well as land cover classification, enabling spatially distributed estimates of meteorological inputs across complex terrain. Inputs to the FIESTA model include meteorological station data (temperature, humidity, wind speed, etc.) and spatial data (elevation, slope, land cover), while outputs include adjusted potential evaporation, fog interception, and wind driven precipitation at a spatial resolution suitable for hydrological modeling.

An in depth analysis of the FIESTA framework has been carried out in a previous study by Cloud Chasers. Therefore, the code is reused to determine the potential evaporation and the fog interception (Hiemstra 2024).

6.4.4 Data preparation and model calibration

To calibrate the canopy water balance model, field data from the HOBO monitoring system must first be collected and prepared. This involves retrieving meteorological measurements from the data logger and processing them into a format suitable for modelling. Once the data is processed, it is used to calibrate the model parameters so that the simulated Effective Precipitation (P_{eff}) closely matches observed values.

Data collection and processing
Meteorological data is extracted using the HOBO logger's unique API token in combination with its `device_id`. All sensors connected to the system carry a unique `sensor_sn`, which is used as a reference to map and identify individual sensor outputs. The initial extraction results in a raw database (CSV file), which contains all recorded sensor values at five-minute intervals. A custom extraction script allows the user to define a desired start and end date to retrieve relevant data.

To make the dataset compatible with the FIESTA model and subsequent hydrological modelling, the following preprocessing steps are applied:

- The time resolution is changed from five-minute to hourly intervals.
- Temperature and relative humidity values from the two different heights are averaged.
- The hourly maximum of relative humidity is picked to create the "maximum Relative Humidity" variable.
- Fog events are identified using the rule that they occur only when vertical precipitation is zero.
- A binary "air rising" variable is defined, assuming that air is rising between 06:00 and 18:00 (i.e., `air_rising` = 1), and not rising during other hours.

As a result, the raw HOBO dataframe is transformed into a cleaned meteorological CSV file that can be directly used as input for the FIESTA functions, with variable start and end-date. This file provides essential variables for estimating horizontal precipitation and potential evaporation with the FIESTA functions.

For the full code, including documentation, see: https://github.com/CloudChasersGT.

Calibration strategy
Calibration of the canopy water balance model involves adjusting the previously discussed parameters (as shown in Figure 38) to find the parameter set that best fits observed data. The key model output is Effective Precipitation (P_{eff}), and calibration aims to minimize the difference between model-predicted and observed P_{eff}.

In practice, observed P_{eff} is calculated from throughfall and stemflow measurements. Since stemflow is not currently monitored, an initial approximation is performed using throughfall data only.

The calibration process is automated by defining reasonable value ranges for each parameter. For every parameter combination within these ranges, the model runs and computes the error between observed and predicted P_{eff} at each time step. The average error over the entire simulation period is calculated, providing a single numerical score for each parameter set. The parameter set with the lowest mean error is selected as the optimal set-up.

This approach provides a flexible and efficient way to adapt the model to local conditions and improve the accuracy of the canopy water balance representation. A standalone calibration script is implemented for this purpose, allowing fast recalibration as new data becomes available. Users can define physical bounds for parameters to avoid unrealistic solutions.

Importantly, the calibration framework is designed to accommodate future improvements. Once stemflow measurements are available, the model can easily be recalibrated using both throughfall and stemflow data, improving the accuracy of P_{eff} estimates.

At present, a complete calibration is not yet feasible due to a limited number of data points and a lack of observed fog events during the monitoring period. However, the calibration script is fully developed and ready for execution as new data is collected.

6.5 Discussion

In-canopy monitoring
The current monitoring set-up reaches to a maximum height of 13.5 meters, which means the measurements are done within the forest canopy. It was decided that the scaffolding tower would have this height, mainly due to the limited budget and time necessary to also build the central pole that is described in section 5. However, several studies (Everson 2014, January, Ramírez et al. 2017, DeLay, John K. 2005) that also monitor the cloud forest canopy water balance use above-canopy measurements. In cloud forests, above-canopy measurements are more reliable for capturing atmospheric processes than in-canopy data. The forest canopy impacts variables like wind speed, temperature, and humidity. Therefore, monitoring these conditions within the canopy does not accurately reflect broader atmospheric processes driving the hydrological processes. Above the canopy, measurements are not affected by the canopy structure, providing more accurate information on factors like evapotranspiration, fog deposition, and precipitation. For example, wind speed and solar radiation are reduced below the canopy. Therefore, it is recommended to alter the set-up to use above-canopy measurements, giving a better representation of the forest's energy and water balance. This could for example be achieved by expanding the scaffolding tower by adding the central pole.

Stemflow set-up
Another key improvement would be the inclusion of a stemflow monitoring system. The current experimental set-up lacks a method for capturing this process, and adding a stemflow monitoring system could provide more accurate data on how water is distributed within the forest floor. This addition would help to refine the canopy water balance model.

Soil moisture gradient
Another potential improvement would be to increase the depth difference of the soil moisture sensors. The current set-up places the sensors at depths of 10 cm and 30 cm, but to gain a better understanding of water dynamics in the soil, it would be beneficial to install them with more distance apart. Furthermore, sensors could be added at greater depths, such as 50 cm or even 100 cm. This deeper monitoring would provide more comprehensive data on how water infiltrates and moves through the soil profile. Understanding soil moisture at deeper levels is particularly important for modelling groundwater recharge and assessing water availability beyond the surface layer, which can vary significantly depending on rainfall events, vegetation cover, and soil types (Bruijnzeel 2004).

Increasing the sensor capacity
The current experimental set-up uses a single HOBO data logger, which can accommodate up to ten sensors. Adding an additional logger would expand the range of data collected. By incorporating more sensors, such as leaf wetness sensors, the system could provide more valuable

insights into canopy dynamics. Leaf wetness is an important factor in understanding evapotranspiration and the hydrological role of canopy cover, and its inclusion would improve the comprehensiveness of the data collected from the forest environment. The added logger could also facilitate the inclusion of a stemflow set-up, and more soil and atmospheric sensors. For example, now only one wind speed and direction sensor is placed, but for evaporation calculations, it would be better to work with a vertical gradient, and therefore to add a sensor at the level of 2 meters.

Sensor limitations and calibration
While the sensors used in the current set-up provide valuable data, their accuracy, response time, and placement are important factors that could influence the reliability of this data. For example, the precision of soil moisture sensors can be affected by the soil type, which could cause deviations from the true soil moisture levels. During this project, the soil sensors were not calibrated, which could be revised. Additionally, the placement of sensors can impact the accuracy of the measurements. Incorrect positioning could lead to non-representative data for the intended study area. Therefore, careful calibration, regular maintenance, and strategic sensor placement are key to minimising these limitations and ensuring the reliability of the experimental data.

Storage measurements
Currently, the study relies on indirect methods through modelling to estimate canopy water storage. However, more direct methods for measuring water storage in the canopy could be implemented to improve the accuracy of these estimates. Methods such as measuring the collection of water in epiphytes could be one way to do this, like the Cloud Chasers I and II did. Due to time constraints, these experiments were not performed in this cycle of the project. Another option would be to use specialised instrumentation for capturing canopy moisture, resulting in a better understanding of how much water is retained in the canopy. Measuring dynamic interception could for example be improved by the use of leaf wetness sensors.

Logging frequency
Currently, data logger submits data every 15 minutes, which is effective for many general observations. However, reducing this interval to 5 or 10 minutes could provide a better view of the temporal variability in water fluxes, particularly during short-term weather events such as sudden rainfall or rapid changes in humidity. Shorter intervals would allow the system to capture more rapid changes in the monitored conditions, which could enhance the understanding of how the catchment responds to these quick shifts in conditions.

FIESTA for horizontal precipitation and evaporation estimation
Fog events in this study are detected using the HOBO set-up, which records when fog occurs. However, the HOBO set-up alone cannot quantify the amount of horizontal precipitation. For this, the FIESTA formulas are applied to estimate the horizontal precipitation and evaporation within the canopy bucket model. This approach has limitations, as the FIESTA formulas rely on empirical assumptions that do not fully capture the complex interactions between fog, rainfall, and canopy structure. Moreover, during rainfall events, fog traps may falsely register fog, making it difficult to distinguish between fog and rain. To avoid this error, fog deposition during rainfall will not be taken into account. This introduces uncertainty into the model outcomes. The FIESTA approach is useful for approximating horizontal precipitation in areas where direct measurements are challenging; the accuracy is strongly dependent on the quality of the input data. Future implementation of more reliable fog measurements would enhance the model's performance. Therefore, the FIESTA approach can be combined with improved fog traps. This increases the reliability of the horizontal precipitation and evaporation estimates.

Canopy Model
It is important to note that the canopy bucket model remains a simplification of the water balance of a cloud forest. The hydrological cycle of a cloud forest is highly complex, involving processes such as canopy interception, evaporation, stemflow, and throughfall, which are only partially represented by the model. Although the current model provides valuable insights into the dominant processes, future research should focus on refining both the fog quantification (via FIESTA and improved fog traps) and the canopy model to better capture the dynamics of cloud forest hydrology.

6.6 Conclusion

This section outlines the importance, development and application of a modular hydrological model tailored for cloud forest environments within a larger catchment system, with the focus of this work on the local canopy water balance of the monitoring tower location. The model is built upon a standardised 'Base Land Class' framework, which defines four key storage layers; interception (Si), unsaturated soil (Su), fast runoff (Sf), and slow groundwater (Ss), common to all land use types found within the Mestela catchment. This modular approach ensures consistency across land use classes while allowing for land-use-specific process definitions.

A specialised cloud forest class is introduced to account for the distinctive dual interception processes of cloud forests, which receive water inputs from both vertical (rainfall) and horizontal (fog/cloud water) precipitation. This requires a detailed canopy water balance model, which separates interception into dynamic and static storages to reflect short-term and longer-term water retention in vegetation and epiphytes. The model outputs effective precipitation (Peff), which feeds into subsurface hydrological processes.

Due to the difficulty in directly measuring fog water input and evaporation, the FIESTA framework is integrated as an initial step to estimate variables based on empirical formulas. Although this introduces uncertainty, it provides a practical means of estimating otherwise unmeasurable inputs.

Furthermore, a calibration script has been developed to optimise model parameters using observed throughfall data. While full calibration is pending due to limited field data, the system is ready to refine once more data becomes available.

The experimental set-up is designed to collect the necessary data for model inputs and the initial calibration and validation of the specific monitoring tower site. It utilises a HOBO data logger system to capture meteorological data with a variety of sensors, such as precipitation, solar radiation and temperature. The data is preprocessed to be used in the FIESTA framework where raw sensor data is converted into necessary variables like potential evaporation and horizontal precipitation. This set-up is essential for providing input into the canopy water balance model and for refining the hydrological simulation.

Nevertheless, several limitations and areas for improvement have been identified with the current experimental and model design:

- In-canopy measurement height: The scaffolding tower reaches only 13.5 meters, limiting the ability to capture atmospheric processes above the canopy. It is recommended that the tower height is extended to improve the accuracy of measurements such as fog deposition, wind speed, and solar radiation.
- Lack of stemflow monitoring: The current system does not capture stemflow, a key process in the canopy water balance since it is part of the effective precipitation. Adding stemflow measurement capabilities would therefore improve the model's accuracy.

- Limited soil moisture depth and calibration: Soil moisture sensors are currently placed at only 10 cm and 30 cm depths. Extending this range to include deeper soil layers (e.g., 50 cm or 100 cm) would provide more comprehensive data on water infiltration and groundwater recharge. In addition the soil moisture sensors have not been calibrated which could introduce errors.
- Sensor capacity: The experimental set-up uses a single HOBO data logger, which can accommodate up to 10 sensors. Expanding this set-up by adding an additional logger and incorporating more sensors, such as leaf wetness sensors, would enhance the system's capacity to monitor important factors like canopy dynamics and evaporation.
- Storage capacities: This study currently estimates canopy water storage indirectly through modelling. However, more direct measurement methods could enhance accuracy. Methods such as measuring the collection of water in epiphytes could be one way to do this, like the Cloud Chasers I and II did.
- Logging frequency: The current 15-minute logging interval may be insufficient to capture rapid changes in hydrological conditions, such as sudden rainfall events or quick shifts in humidity. Reducing the logging frequency to 5 or 10 minutes would allow the system to capture these dynamic changes more accurately.
- Enhance model accuracy: Both the FIESTA framework and the defined Canopy Model remain simplifications of complex processes. Therefore, calibration and modelling improvements are essential. This includes, for example, refining fog quantification methods or improving the formulas used to split hydrological fluxes. These steps are crucial for improving model accuracy and providing more holistic insights into the water balance of both the cloud forest and its role within the catchment.

While the current hydrological model set-up provides a valuable foundation for understanding cloud forest water dynamics, it remains a simplification of the complex processes at play. Future improvements in both the modelling framework (particularly fog and interception processes) and the experimental set-up (including sensor calibration, monitoring infrastructure, and data resolution) will enhance the precision of the model and provide deeper insights into cloud forest hydrology. These advancements will be critical for refining predictions of water availability, groundwater recharge, and the overall ecological health of cloud forests.

7 Objective C: The role and value of monitoring within the cultural context of CCFC and its stakeholders

7.1 Introduction

Understanding the hydrological cycle of the Mestelá River catchment through the implementation of a long-term monitoring tower forms the technical foundation of our multidisciplinary project. However, for this infrastructure to have a meaningful, long-lasting impact, it must be embedded within the social, cultural, and institutional realities of the local context. A technically functioning tower alone does not guarantee sustainable outcomes if community engagement, trust, and ownership are lacking.

Given the significant cultural and socio-economic differences between the TU Delft research team and the local CCFC community in Alta Verapaz, we emphasise the importance of intentional community collaboration and shared ownership. The long-term sustainability of the hydrological monitoring system hinges on the capacity and motivation of CCFC and connected stakeholders to independently maintain, adapt, and integrate the technology into their ongoing work once external actors step away. This is not merely a technical transition, but a social handover, which is a process that, as identified in the literature on post-project sustainability challenges (Myers et al. 2014; Fahri et al. 2020), carries a real risk of breakdown when responsibility is not meaningfully transferred or embedded within local structures.

The previous MDP team, Cloud Chasers II, made a valuable contribution by conducting a stakeholder analysis and proposing a conceptual engagement framework. Their work provided insights into the multi-stakeholder dynamics of the cloud forest region and offered guidance on how inclusive communication and collaboration might be approached. However, our project marked a significant shift in scope and ambition. By constructing a permanent monitoring tower with a concrete foundation, designed to serve the CCFC over the next decade, we introduced a durable, physical infrastructure that comes with long-term responsibilities for upkeep, integration, and expansion. As a result, our engagement strategy had to extend beyond conceptual frameworks and into the realm of practical implementation and capacity-building.

To develop this strategy, we drew on two central sources of insight: the cultural and spiritual worldview of the Q'eqchi' Maya community in Alta Verapaz, and existing academic frameworks on community engagement and project sustainability. These two sources provided the foundation for how we approached collaboration, ownership, and long-term responsibility in the implementation of the hydrological monitoring tower.

This chapter therefore begins with an exploration of the Maya cultural context, including its cosmovision related to water and forests. Following that, we review relevant literature on community engagement, behavioural change, and post-project sustainability. This is followed by an overview of the activities we implemented on-site, including a summary of the workshops and engagement strategies developed in collaboration with CCFC. Finally, we reflect on what we learned through this approach, both in terms of outcomes and challenges.

7.2 Maya cultural context

The population of Alta Verapaz is mainly composed of Q'eqchi people. The Q'eqchi is the second largest Mayan ethnic population in Guatemala, with Alta Verapaz being one of the highly concentrated Q'eqchi areas. The Maya civilisation flourished in Guatemala in the pre-Columbian era from around 2000 BC to 1500 AD, until the Spanish Conquest. The civilisation was advanced in its writing, art, architecture, mathematics, astronomy and calendar. The Maya region comprised what today is southeastern Mexico, all of Guatemala and Belize, and the western portions of Honduras and El Salvador. The Maya writing system in the pre-Columbian Americas was the most sophisticated of its time, with complete history archives being recorded in books. However, these have all been destroyed by the Spanish Conquest, with only three books remaining, which are currently all being stored in Europe. Hence, much information on the rich history of the Mayan civilisation has been lost. Despite this loss, there are many aspects of Mayan culture that have lived on and are embedded in the Guatemala of today, such as traditions, beliefs, language, cuisine, agricultural practices, and calendars. For example, in Guatemala, there are still twenty-two Mayan languages that are actively spoken. However, it must be noted that an overarching Mayan culture cannot be grasped in general terms, though there are certain recurring aspects throughout different contemporary Maya cultures. At the base stands the Mayan Cosmovision, which forms a deep-rooted worldview shared by different modern Maya groups. For this project, it has been tried to deepen the understanding of this cosmovision and its presence in Alta Verapaz. Besides reading, watching movies and visiting museums, most of the information presented in this section stems from the Q'eqchi women working at CCFC, Ajq'ijab (Q'eqchi spiritual guides), and the families from the Sesarb aldea that we stayed with in a homestay. Below, some aspects of the Mayan worldview are highlighted that are mostly related to the research on cloud forests from this project.

7.2.1 Cosmovision

The Mayan epistemology is centred around many different dualities, such as light and dark, life and death, men and women, and humans and nature. Between these opposites, an equilibrium is sought to obtain harmony. Regarding the human-nature dualism, this translates to a deep relationship between humans and the natural world. Humans are seen as stewards who have the responsibility to take good care of the Earth. In the old Mayan civilisation, a profound respect for the environment was, for example, expressed through their agricultural practices. The milpa system, which is still used nowadays, entails the rotation of crops and giving land time to restore itself. Hence, a reciprocal relationship with the land is formed based on a balance between harvesting and care-taking.

Besides the importance of dualities, another central belief in the Mayan cosmovision is that everything that exists holds life. Hence, not only animals and plants but also entities that are not often regarded as living; such as soil, air and water. Everything is evolving and in motion. The ancient Maya believed that the natural world was imbued with spiritual energy, and that this energy connected all beings, animate and inanimate. Water, in particular, was considered a sacred element that represented life's flow and the cyclical nature of existence.

Water was not simply a resource for the Maya, it was connected to the gods and the ancestral spirits, and many of the sacred sites were located near bodies of water (such as caves, cenotes or rivers) because they were thought to be portals to the underworld, Xibalba, where the ancestors were. The Maya understood that water was flowing through all aspects of all life, interconnecting everything in the universe. The rain god, Chaac, was central to Mayan rituals, often honoured in ceremonies to ensure agricultural fertility and the balance of natural forces.

The duality of water as both a giver and a taker of life was also recognised. Water was the source of fertility and prosperity, but also capable of destruction through floods or droughts. As such, the Maya sought to live in harmony with water, seeing both its nurturing and destructive sides. This understanding is reflected in their practices: for example, they developed complex systems of rainwater collection and irrigation, which we have been able to see the remains of in Tikal National Park.

In Maya cosmovision, humans were not seen as separate from nature, but as a part of it. The idea that humans must live in balance with the Earth was deeply embedded in their worldview, and this balance extended to water.

7.2.2 Water as a mirror of life's interconnectedness

Water's role in the Mayan worldview goes beyond its material value; it embodies the essence of life itself. In the Maya understanding, water is both a physical and symbolic element. It is a connector, of humans to gods, of humans to the land, and of the past to the future. The cyclical flow of water, from rainfall to rivers to underground aquifers, mirrors the cycle of life, death, and rebirth that the Maya saw in the world around them. Water is ever-present, constantly moving, and, in its movement, it brings both life and death, renewal and decay.

This perspective is also reflected in the following quote:

> *"It is not possible to find a new way of living that eliminates current waste and pollution of water without understanding how the ancient cultures of Guatemala feel, perceive and think. Surely, a new consciousness in the country, with respect to the universe and life, must make a change that is not just a change of actions, but also a change of paradigm that will mean a new way of organizing thought: To understand man is not to extract him from the universe, but to situate him inside of it."* - Matul 2016, March

This perspective calls for a deep reimagining of the place of humans in the world, namely, seeing humans as part of nature, not separate from it.

In the ancient Maya worldview, nature and all of its elements, such as water, air, and soil, exist in a constant state of relationship. They are not isolated, but interconnected, which should remind humans that our survival is dependent on the well-being of the Earth. This interconnectedness emphasises the need for reciprocity, balance, and responsibility in the way we connect with the natural world.

7.3 Literature: community engagement and the long-term sustainability of environmental technologies

Designing an environmental monitoring system is as much a social project as a technical one. Over the last decade, a growing body of literature has emphasised that for technologies to have a sustainable impact, particularly in contexts with social, cultural, and economic complexity, they must be meaningfully embedded in the communities they are intended to serve. This section outlines the main conceptual frameworks and findings that guided our thinking around community engagement, social handover, and long-term sustainability in the context of hydrological monitoring at CCFC in Alta Verapaz.

Long-term sustainability and the post-project phase
A common but under-addressed challenge in international development is the "post-project sustainability gap": what happens when project teams leave, and the responsibility for ongoing management is transferred to local actors. Myers et al. 2014, in their evaluation of development outcomes in Indonesia, note that even well-implemented projects risk stalling if follow-up structures, local ownership, or institutional support are lacking. Similarly, Negi and Sohn 2022, reviewing over 400 GEF-funded projects, found that sustainability beyond the project period is strongly tied to stakeholder buy-in, continued resource availability, and local capacity.

The concept of a "social handover", as described by Fahri et al. 2020, frames this transition not as a technical transfer but as a shift in responsibility, accountability, and legitimacy. They emphasise that successful handovers depend on several post-handover criteria: continued community interest, adaptability of the intervention to local systems, and the presence of champions or institutional anchors who can carry the project forward.

Inclusive stakeholder engagement
Within the research domain, inclusive stakeholder engagement is increasingly seen not just as good practice but as a prerequisite for ethical and effective knowledge production. Lieu et al. 2023 highlight that many participatory projects fall short by failing to address structural inequalities or privileging certain knowledge systems, especially Western, scientific ones, over local or Indigenous perspectives. Their concept of equitable knowledge co-production calls for stakeholder engagement that recognises epistemic justice (valuing different ways of knowing) and recognition justice (fair inclusion of marginalised voices).

This is particularly relevant in our context, where environmental data collection intersects with Q'eqchi' Maya worldviews that emphasise reciprocity, respect, and the interconnectedness of life. In such a setting, participatory practices must go beyond consultation and actively build shared meaning, ownership, and trust across cultural boundaries.

Behaviour change and levels of use
For community engagement to lead to long-term sustainability, it is essential to recognise that individuals and groups interact with new technologies in different ways. Contzen et al. 2023 propose a behavioural model that categorises user interaction into three levels: passive, engaged, and active use. These levels reflect increasing degrees of awareness, responsibility, and behavioural change, and offer a practical lens for designing targeted engagement strategies.

In the context of our project, these levels help define the role of the hydrological monitoring tower in the community and how users might relate to it over time.

- Passive use, rooted in acceptance, involves simply informing people about the tower's purpose and operation. This requires no action from them, but ensures that they understand the technology and are comfortable with its presence. Data is collected and analysed externally, and users benefit from the outputs (e.g., rainfall trends or flow data) without having to alter their daily routines.
- Engaged use, grounded in support, goes a step further. Users not only understand the technology, but also begin to contribute, helping with basic maintenance tasks or integrating tower data into CCFC workshops, research projects, or educational materials. This type of use enhances the relevance of the tower within local programs and fosters a sense of shared responsibility.
- Active use, associated with behavioural change, represents the deepest level of engagement. Here, stakeholders go beyond the existing system to create new uses and extensions. This might include installing additional sensors (e.g., acoustic monitoring), modifying the platform to address emerging research questions, or using the data to inform local environmental planning. At this level, the tower becomes a tool for innovation and community-led inquiry.

Planning engagement across these three levels will allow us to meet different kinds of users and stakeholders where they are, respecting their time, interests, and capacity.

Data value, trust, and appropriateness in water monitoring
Veness and Buytaert 2025 underscore a key challenge in environmental data projects: data only gains value when it is used and trusted. Their research shows that sensor networks often fail in low-resource contexts not due to technical issues alone, but because of unclear ownership, low data accessibility, or perceived irrelevance. If communities don't understand or trust

the data, or see no meaningful way to act on it, the system will be underused or even dismantled.

This insight is echoed in previous evaluations of hydrological monitoring (Bremer et al. 2020; Kolinjivadi et al. 2017), which argue that the value of monitoring technologies is not in the data alone, but in the social processes they support, such as dialogue, decision-making, or community learning. In this light, promoting trust, transparency, and open access becomes as important as installing functioning hardware.

Behavioural techniques and cultural realities
Finally, our engagement strategy was also informed by behavioural models such as the RANAS framework, which focuses on key psychological drivers of behaviour change: Risk, Attitude, Norms, Ability, and Self-regulation (Contzen et al. 2023). In the CCFC context, feedback from community partners emphasised three interconnected priorities:

- Trust: Building emotional and relational trust takes time, especially in post-conflict settings like Guatemala.
- Ability: Open access and low barriers to use are crucial to empower non-scientific stakeholders.
- Ownership: Involving users in maintenance and decision-making increases their sense of responsibility.

This review of theories and frameworks shaped the way we approached community engagement throughout the project. In the next section, we describe how these concepts were put into practice, through workshops, interactive activities, and strategies to support long-term ownership of the monitoring tower at CCFC.

7.4 Results: workshops and activities at CCFC

With input from learnings on Maya culture, as well as community engagement and project sustainability literature, we organised a brainstorm together with our team member Yoselin for the overall planning and content of the workshops. Ideas were formed first and afterwards refined and connected to the different RANAS factors. We used a MIRO whiteboard to support creative thinking and visual support. Later, feedback was sought from the CCFC director to make sure the planning would fit into the schedule of the team.

Maya permission ceremony
Throughout the project, we gradually deepened our understanding of the Maya cosmovision, particularly the Q'eqchi' perspective on the relationship between humans and nature. Two key experiences were especially inspiring regarding how to apply this in our project. Firstly, in the first days of the project, we had the opportunity to visit a cave at the CCFC site with Marta Macz Pacay, a Q'eqchi' spiritual guide. During the visit, she taught us about the spirituality of caves and how they are a place to communicate with our ancestors or energies. Through the burning of candles, we connected with the mountain that the cave was a part of. Secondly, we attended the opening ceremony of a big agroecology conference that was held at CCFC in the second week of our project. This took place in another cave at the CCFC property and involved offerings, chants and candle burning. This, as well, was a way to connect with the surroundings and with each other as a group. These two cave visits brought inspiration to participate in a Mayan ceremony to ask for permission to construct the monitoring tower on the mountain. Especially since some of the construction activities were invasive to the nature and soil of the mountain, they could not be started without consultation. This idea was communicated to the CCFC teacher team and the construction team, and all consulted persons agreed that a ceremony was an important step before starting to build.

Goal
To respectfully seek permission from the mountain and surrounding environment before beginning construction, aligning the project with local spiritual and cultural values. Additionally, the ceremony aimed to enhance the team's connection with the forest, mountain and water.

Output
A ceremony was held in one of the caves at CCFC, led by spiritual guides Marta Macz Pacay and Mario Caal Jucub. It included traditional offerings, fire reading, attention to participants' 'navales' (personal energies), and collective sharing. The full participation of the CCFC women's team strengthened the sense of community and spiritual alignment, setting a respectful and intentional foundation for the construction phase.

Mujeres fuertes interviews
As an integral part of our weekly newsletters, we interviewed two women of the CCFC team every week. The rubric's name was 'mujeres fuertes' ('strong women'), since this is what we always called each other as a team. Each interview followed a consistent set of questions:

- 'Where are you from?'
- 'What do you study?'
- 'What do you value most about the forest at CCFC?'
- 'How do you like to spend your free time?'

Goal
The primary goal of these interviews was to get to know the team better. Not only to get used to each other as team members, but also to increase understanding of how they relate to their work at CCFC and what they find important.

Outcome
These informal conversations provided valuable insights into the team's personal interests, cultural backgrounds, and motivations. For example, we noticed the strong motivation of many of the women to eventually return and contribute to their home villages by working there.

The 'mujeres fuertes' interviews not only deepened our understanding of the team's values and backgrounds but also helped to bond and build mutual trust. During the final evaluation, both Sara and Yoselin highlighted the interviews as a key factor in creating a feeling of inclusion and strengthening the team dynamics throughout the project.

Co-creation 'values of water and the forest' poster
This low-effort activity invited team members to share their thoughts on the relationship between water, the forest, and the goals of our project. This was done by making a poster with questions, and placing the poster in a central location. Throughout our project, the women of the CCFC team could contribute their thoughts and answers to these questions by writing on the poster. The following questions were used:

- 'What is the value of water?'
- 'How are water and the forest connected?'
- 'What is the source of water in your community?'
- 'How do we take care of water?'

Goal
The goal of this activity was to gather insights on how the CCFC women viewed relationships between water and land. Thereby, it should increase understanding of how the project would relate to these values.

Outcome
The output of this activity was the poster and the written responses that were added by the CCFC women. The input gathered helped us better understand the team's perspectives and values, and it served as a foundation for the next workshop.

Hypothesis workshop
This workshop consisted of two parts: a short presentation and demonstration of the experimental set-up that was set up in the valley, as shown in Figures 39 and 40, followed by breakout groups where participants formulated their own hypotheses and posed questions.

Goal
To involve the community in the research process and learn from them by encouraging knowledge exchange and co-creation of research questions.

Outcome
Participants shared valuable insights and ideas. For example, one hypothesis was about the impact of extreme weather events, which was something we had not thought about ourselves. This was eventually a reason to install a lightning rod to the tower construction.

Figure 39: Photo of presentation of the experimental set-up (Cloud Chasers IV, 2025)

Figure 40: Photo of demonstration of the experimental set-up (Cloud Chasers IV, 2025)

DIY solar shields workshop
In this fun, hands-on activity, participants built their own solar radiation shields using simple materials sourced from a local store, as shown in Figure 41. These shields were later installed on the towers, making the activity both practical and engaging.

Goal
To connect the team directly with the instrumentation and spark interest through doing.

Outcome
The DIY workshop increased understanding of the tools used in the field. From the evaluation with Sara and Yoselin, it was taken away that adding a tangible part to the construction of the tower enhanced the sense of ownership of the tower for the CCFC women.

Figure 41: Photo of DIY solar shields workshop (Cloud Chasers IV, 2025)

Site visit and final presentation
In the final week of the project, we organised an event that brought together various stakeholders, including CCFC's network and university partners, to share outcomes and start a dialogue on future research opportunities. The event consisted of a visit to the site in the morning, followed by a final presentation in Spanish about the project. The presentation included the general mission and objective of the project, explanations of the reasoning behind decisions for the tower construction and the experimental set-up, and reflections and learnings of our weeks at CCFC.

Goal
To present our findings, enhance collaboration with local partners, and explore new project directions for the future. Furthermore, to receive feedback from local experts on the used approach and on the following steps to take.

Outcome
This event strengthened connections between local stakeholders and academic institutions, and enabled continued engagement. The attendees included the CCFC team, the team of a nearby park/research center, spiritual guide Marta, people from local agroecology organisations, and various Guatemalan researchers who had presented their work to us throughout our time at CCFC.

Maintenance/data workshop
A workshop was organised about the maintenance of the tower and experimental set-up, as well as on the usage of gathered data. This workshop was tailored for the smaller CCFC team responsible for continuing the project, and consisted of a presentation, as well as a familiarisation session with the maintenance Excel sheet.

Goal
To equip the core team with knowledge and strategies to sustain and manage the monitoring set-up.

Outcome
The activity resulted in productive discussions around maintenance needs and potential improvements. The reaction to the maintenance Excel sheet was very positive, as it provides detailed descriptions and planning of aspects of multi-year maintenance steps. Moreover, the placement of the data gathered by the tower's experimental set-up within the bigger picture of hydrological models was useful. However, the lack of gathered data meant that this remained abstract, resulting in the need for ongoing discussion about data usage with the complete CCFC team.

7.5 Discussion

In this section, we critically examine our engagement strategy, based on our own reflection, but also from external parties (CCFC team and directors), so that future projects (especially next Cloud Chasers) can learn.

Academic theory versus real life
While academic literature provided a valuable starting point for shaping our engagement strategy, the realities of working on-site at CCFC revealed important limitations of applying theory in a prescriptive way. Models such as RANAS, concepts like equitable co-production, and frameworks for behavioural change and sustainability all offered useful tools, but none could fully prepare us for the depth, nuance, and unpredictability of real-life community interaction.

One of the clearest examples of this was the concept of trust. In theory, trust can be "built" through transparency, consultation, and consistent communication. In practice, however, it was something that grew slowly and organically, through small, informal moments: having meals together, chatting during breaks, taking interest in the lives of the CCFC team. No academic framework accounted for the importance of just being human with each other.

A second insight came from our use of "fun" as a strategic principle. While not mentioned in most behavioural or participatory frameworks, fun was a central component of how we designed our workshops and promotional activities. This was not only because it made sessions more enjoyable, but also because fun is deeply embedded in CCFC's philosophy of exploratory learning, the belief that people learn best through curiosity, movement, and doing. Whether it was building DIY solar shields, sharing jokes while painting a poster, or hosting dance nights, fun turned out to be one of the most effective tools for generating engagement, lowering barriers, and fostering a sense of ownership. Yet, in the literature we used, this element is surprisingly absent.

Thirdly, we found that many theoretical assumptions, particularly those developed in Western academic settings, do not easily translate to the cultural and cognitive frameworks of the Q'eqchi' community. For example, the RANAS model includes "perceived risk" as a central motivator for behaviour change. But this assumes a form of abstract, future-oriented, cause-and-effect thinking that does not align with how many people at CCFC make sense of the world. As one of the directors pointed out, climate risks or water scarcity are often experienced as present realities rather than distant projections, and are processed more through direct experience than abstract reasoning. For this reason, we chose not to emphasise risk or cost-benefit arguments in our workshops, and instead focused on relational, embodied, and exploratory forms of engagement.

Incorporation of local knowledge
One of the most valuable takeaways from this project was learning how to genuinely recognise, trust, and incorporate the local knowledge that already existed at CCFC. Although we began the project with a clear awareness of our position as an external research team and the importance of collaboration with local partners, it still took time for us to fully act on that awareness in practice.

A clear example of this was the construction phase of the monitoring tower, particularly around the design of the rebars. While we had spent considerable time thinking through technical options and alternatives, it was Eusilivio, one of CCFC's most experienced team members, who proposed a better solution in a matter of minutes. Looking back, we realise that moments like these were not isolated; they happened regularly. Still, it took us some time to develop the confidence to truly rely on and build around that local expertise.

This gradual trust-building was likely shaped by differences in how knowledge is expressed and valued. In our academic environment, we're trained to prioritise planning, documentation, and tools like SketchUp, so when we began creating digital tower designs early on, it felt like progress. But these digital drawings didn't translate well into collaboration with the CCFC team. In fact, working in SketchUp early on created more distance: it limited spontaneous discussion, and made it harder for hands-on contributors to get involved. Looking back, if we had started co-designing the tower in an open-ended, sketch-based way with Eusilivio and others from the very beginning, the process might have been both faster and more collaborative. It's easy to assume that "more people and more opinions" will slow things down, but in this case, that assumption proved wrong.

Another reason this shift didn't happen instantly is cultural: in Guatemala, and particularly within Q'eqchi' communities, people are often quite reserved, and it takes time to build the kind of relationship where they feel comfortable offering suggestions or asserting their knowledge. This means that it's not enough to just "be open" to local input; you also have to ask for it deliberately, and create the space for it to emerge.

In the end, we feel incredibly grateful to have worked alongside such experienced and thoughtful people. The lessons we learned from collaborating with Eusilivio and the rest of the CCFC team have been some of the most important of the entire project. For future projects, we strongly recommend actively inviting local perspectives into the design phase right from the start, not just to improve efficiency, but because it leads to better, more grounded, and more meaningful results.

Cultural differences
When reflecting as a group, the Mayan ceremony was one of the most fruitful experiences of this project. It brought us in contact with knowledge systems that we had not encountered before, and showed us a profound respect for nature and surroundings. It challenged our initial idea of an 'engineering project', since the respect for nature is not something that we had learned about in our curriculum. Therefore, we also noticed it was challenging to truly take the ceremony and its outcomes seriously. Since we do not share the culture, it is difficult to truly feel the need to ask for permission. It was an interesting and new experience for us, but we can not say that we felt as connected with the ritual as the rest of the team. Two examples highlight how we struggled with truly opening ourselves to a new perspective.

Firstly, in the previous communication with the spiritual leaders, it was communicated that a rooster had to be offered during the ceremony. As a group with four vegetarians, we largely felt that killing an animal was out of line. Somewhere, we did not take the ceremony seriously enough to feel that it was necessary to kill a rooster. Or, we put our own views on animal well-being above the role that this played in the Q'eqchi' culture in this situation. Secondly, during the ceremony, a message was given through the form of the fire that there were challenges in the communication within our team. We listened to the comment, but did not do anything with it. After a couple of days, it dawned on us that we should take this advice more seriously, and we discussed it in a meeting with the whole team (including our Guatemalan team members).

Besides broadening our perspectives and reflecting on our biases, the Mayan ceremony was also a way to connect with the CCFC team. Everyone participated actively in the ceremony, and besides the focus on the construction project there was space for individual issues. This shared experience added to the trust within the team.

A second cultural insight emerged during our final reflection session with the CCFC directors. When we suggested reviewing the project's technical "outputs" separately from the team process, he responded by quickly saying to be "not so much interested in results". For CCFC, what matters most is the people involved and the relationships built along the way. To put it in other words, he said: "It's not the garden, but the gardener that counts".

This comment was not meant as a critique, but rather as a gentle reminder of what truly matters in CCFC's work. It also highlighted a subtle difference in worldview: while we had always tried to keep the community and process in focus, our engineering backgrounds naturally led us to frame impact in terms of outputs, efficiency, and results. This moment helped us reflect on how deeply that mindset is embedded in our academic training and how different the guiding values can be in a context like CCFC, where community, relationships, and care for people and nature are central.

The role of the workshops and internal communication

One of the most positive reflections shared by the CCFC directors was on the way we involved the women's team in our project activities. In doing so, we honoured the core of "Community" in Community Cloud Forest Conservation. Several team members expressed that their sense of trust and connection grew through the workshops and activities, and that they felt genuinely involved in shaping the project, not just supporting it from the sidelines.

This connection was built not only through the workshops themselves, but also through the informal moments that surrounded them. Shared meals, time spent relaxing together, and everyday conversations created a sense of equality and ease. Our group's Spanish language skills and open, approachable attitude played a big role in creating a comfortable and collaborative atmosphere from day one.

At the same time, a useful point of feedback was that future engagement and communication strategies could benefit from more attention to the Q'eqchi' language. For many of the women on the team, Q'eqchi' is their first language and the one in which they feel most at ease. Investing in bilingual or Q'eqchi'-specific materials, activities, or facilitation could increase accessibility and inclusivity even further.

There's also room to strengthen internal communication and coordination, especially in relation to the research structure. While day-to-day collaboration on campus was smooth, the communication with Luis, the research coordinator and primary institutional anchor, could have been more consistent. In future projects, setting up regular check-ins and clearer communication channels with part-time coordinators like Luis, especially when they hold long-term responsibility for project continuity, will help ensure that knowledge transfer and follow-up actions are aligned.

7.6 Conclusion

Before starting our fieldwork in Guatemala, this objective was seen as one of the most important components of the project. We aimed to engage meaningfully with the CCFC community and integrate our technical work within the local cultural and institutional context. Throughout the project, we focused on building collaboration and ownership through a wide range of activities, from the Maya permission ceremony to co-designed workshops like the DIY solar shields and the "values of water and the forest" poster. These efforts were grounded in both local knowledge and relevant academic frameworks, but our experience also highlighted the limitations of theory when working in real-life contexts. Trust and engagement proved to be gradual and relational processes, shaped more by informal interaction and mutual curiosity than by structured models.

Looking back, we are proud of the results, both in terms of the technical outcomes and the relationships established during our time at CCFC. The engagement strategy helped foster a sense of shared responsibility, and our open approach allowed for valuable contributions from local team members that improved both design and implementation. For future teams, we recommend taking initiative in proposing activities and workshops, even without certainty about their success. As we experienced, enthusiasm, openness, and a collaborative attitude are valued at CCFC, and can lead to meaningful learning and cooperation on both sides.

8 Objective D: Future maintenance and expansion

8.1 Introduction

For a hydrological monitoring system to remain effective over time, consistent maintenance is essential. Especially in remote and humid environments such as the cloud forest of Alta Verapaz, equipment is exposed to challenging conditions, ranging from high humidity and intense rainfall to biological growth and physical wear. This became evident in previous Cloud Chaser projects, where several monitoring instruments eventually failed due to the absence of a well-communicated maintenance plan. Over time, this resulted in a loss of valuable data and a disconnect between the intended long-term monitoring goals and the day-to-day realities of system upkeep.

There is a need for a plan that is designed to be user-friendly, adaptable and well communicated across future research groups and within CCFC to ensure continuity of the monitoring set-up. In addition, expanding the sensor network over time enhances the long-term sustainability and adaptability of the system, ensuring it remains relevant for evolving research and conservation needs. Therefore, the objective of this chapter is to provide recommendations for future maintenance, communication and expansion of the set-up, to support long-term functionality and facilitate further environmental research.

8.2 Methodology

Before drafting the maintenance plan, interviews with the CCFC staff were conducted to gain insight into their preferences and past experiences. These conversations concluded that, while clear task descriptions are an obvious necessity, there is also a need for time estimates and a checklist, all preferably in Excel as it is familiar and easy to use. In addition, to make the plan truly useful for CCFC and local staff, translation into Spanish is essential.

The interviews, along with own field observations and sensor manuals, formed the basis for the design of the maintenance plan. The plan was developed in Excel and consists of four structured tabs. The first tab provides an overview of all components that require maintenance, including their physical locations and heights. This overview helps users quickly identify where each component is situated.

The second tab presents a detailed breakdown of maintenance tasks per component. Each row includes the component's category, the specific component name, the task to be performed, a clear task description, the estimated time required, the recommended frequency, and a list of required tools or materials. The table is fully filterable by both category and sub-category, which makes it easy to extract.

The third tab generates a maintenance schedule, based on the frequencies defined in the second tab. It clusters tasks that share similar frequencies so they can be executed during the same visit. Since the site is remote and travel time is considerable, the 3C Concept (Centralise, Cluster, Coordinate) from Kammouh et al. 2021 is applied to reduce the total number of visits needed. By grouping non-critical but flexible tasks around fixed maintenance moments for central components, the plan is optimised to be time-efficient.

Finally, the fourth tab functions as an operational task check-list, which can be filtered by maintenance round (e.g., weekly, monthly or yearly). This allows users to generate checklists for each visit, ensuring that all necessary tasks are carried out in one go and any observations or issues can be noted for future follow-up.

8.3 Results: maintenance plan

The resulting maintenance plan is included in Appendix E and was presented to CCFC staff, who appointed a responsible team member for its implementation. The plan is structured in Excel and consists of four interconnected tabs: a component overview, a task breakdown, a scheduling calendar and a printable checklist. The plan begins in week 26 of 2025 and runs through week 52 of 2029. After this period, the structure can be reused for subsequent cycles.

The plan covers essential activities to maintain the monitoring system, including cleaning, inspection, structural upkeep, sensor checks and data logger maintenance. To ensure completeness, all sensor manuals are reviewed, and include not only standard maintenance actions such as cleaning, but also long-term tasks like sensor verification. All observations have been incorporated into the plan. For example, during the project, a branch fell on a guy wire during a storm, breaking a tensioner, as shown in Figure 42. This showed the importance of weekly or post-storm checks to detect any damage or malfunctioning components.

Figure 42: Example of failed tensioner during storm as input for maintenance plan (Cloud Chasers IV, 2025)

The Excel file allows filtering by category or component, which makes it easy to extract, for example, all sensor-related tasks or only those linked to the scaffolding.

8.4 Discussion

The development of a maintenance plan is an important step toward ensuring the long-term functionality of the monitoring system. The plan's success ultimately depends on how it is implemented and maintained over time. Several points for consideration have emerged during the process.

First, it is important to note that the maintenance plan is not static and final, but intended to remain flexible and dynamic. It should be updated based on experience, observed issues and improvements identified during execution. The Excel format allows for easy adjustment of components, task descriptions or planning intervals, supporting the continuous relevance and reliability of the monitoring set-up.

Second, while most tasks can be performed independently by CCFC, few tasks require technical expertise and specialised tools, particularly sensor verification and troubleshooting. It is recommended that more advanced sensor procedures be carried out in collaboration with future visiting research groups, and the schedule may be adjusted accordingly.

Third, it is recommended that a digital maintenance record is kept to track when tasks have been completed and by whom, including any anomalies or issues noted during site visits, for which the checklists can be used.

Fourth, while the technical aspects of the plan are comprehensive, its long-term effectiveness will also depend on motivation, ownership and continuity within CCFC. To support this, annual maintenance training sessions and review moments, either internally or with the help of research groups, could help embed the plan into routine operations and foster a sense of ownership.

Finally, in addition to regular maintenance, the current set-up also offers opportunities for future sensor expansion to serve broader research and conservation goals. During the final presentation, representatives from Ranchitos del Quetzal expressed interest in the potential use of the tower for monitoring quetzal populations, for example, through the installation of acoustic sensors or camera traps. This illustrates how the tower can evolve into a multi-purpose research platform, supporting both hydrological studies and biodiversity monitoring. Integrating such additions into the maintenance and data frameworks will require coordination, but also presents an exciting opportunity for interdisciplinary collaboration and wider impact.

8.5 Conclusion

The development of a maintenance plan is essential for securing the long-term functionality of the hydrological monitoring set-up and ensuring the collection of high-quality data for research and conservation well beyond the duration of this project. Built on insights from interviews, field observations and sensor manuals, the resulting plan is both practical and adaptable, covering routine and advanced maintenance tasks. The involvement of CCFC staff throughout the design and implementation process enhances local ownership, which is a requirement for the long-term success of the system. By treating the plan as a living document, open to adjustments and local insights, it becomes a sustainable tool that can evolve with changing conditions and new experiences in the field.

With the potential to integrate new research tools, the monitoring tower can grow into a platform for interdisciplinary research. As such, this framework not only supports long-term water data collection, but also opens the door to broader conservation impact.

9 Conclusion and key recommendations

9.1 Conclusion

This multidisciplinary research project successfully designed and implemented a 13.5-meter scaffolding tower for hydrological monitoring in the cloud forest of Alta Verapaz, Guatemala. The tower forms a foundation for future hydrological and environmental research, providing a durable structure for long-term data collection (a period of at least 15 years). Through four different objectives, we have addressed both technical and socio-cultural challenges of this project, and thereby answered the following main research question:

"How can the design and implementation of a long-term hydrological monitoring tower in the cloud forest of the Mestelá River catchment support both effective hydrological data collection and sustainable local ownership?"

In objective A, the completion of the scaffolding tower is the primary achievement. The design process aimed to balance engineering principles with local realities, resulting in a structure that is not only technically sound but also contextually appropriate for the site. The collaborative construction process, which involved CCFC staff and local builders, was crucial to overcoming field challenges, particularly the uneven terrain. While this part of the project took significantly longer than expected, it has resulted in a modular and flexible structure that can be expanded in the future. For example, while the tower now has a height of 13.5 meters and therefore reaches to within the canopy, the calculations have already been done to enable expansion to 25 meters through the addition of a central pole. Thereby, the monitoring set-up could reach above the canopy, improving the representativeness of the canopy measurements. Hence, future teams can build upon the existing structure, enabling the tower to have long-term value for environmental research.

Objective B integrated the experimental set-up in the tower and the use of models to eventually monitor the cloud forest's hydrological processes. The set-up has been installed and is currently effectively collecting data. Furthermore, a preliminary canopy water balance model has been developed that is compatible with the FIESTA model, operating at a landscape scale, and the catchment-scale Flex Topo model. However, the lack of sufficient collected data means that these tools cannot yet be fully verified or calibrated. Until September, data will be collected, and it is anticipated that this can be used by the next group of Cloud Chasers to refine the models and enhance their functionality. Additionally, the set-up can be expanded to include more sensors, particularly for monitoring above the canopy, which will offer a more comprehensive view of the hydrological cycle.

The success of objective C lies not in the technical outcomes but in the meaningful engagement with the local colleagues and stakeholders. The outcome of this objective is not something that can be measured, it is something that is felt and reflected upon. By us, but more importantly by the CCFC team and other local stakeholders. The importance of integrating local knowledge into scientific efforts was a key theme throughout the project. From the daily collaboration with our local team members Sara, Yoselin and Luis, to the attendance of the Maya permission ceremony, to the practical construction of the tower with a local team. We learned a lot about how local perspectives, especially those rooted in cultural and spiritual values, were critical to the success of the project. We believe that the different workshops, interviews, but also bonding moments outside of working time have resulted in mutual learning. They have created a sense of shared responsibility and trust, creating a base for long-term cooperation and friendship between the project team and CCFC.

Finally, objective D focused on ensuring the sustainability of the monitoring system. By developing a maintenance plan that includes both routine and advanced tasks, the groundwork has been laid for the long-term functionality of the system. This plan is designed to be adaptable, accommodating local needs and changes over time. The involvement of the CCFC team in the creation of this plan ensured inclusion of local expertise and ownership, which is crucial for its continued success. Moreover, the potential for adding future research methods further enhances the tower's value for further interdisciplinary research.

Throughout the project, a key overarching theme was the importance of local knowledge and collaboration. Whether it was in the design and construction phase, the Maya's vision on the interconnectedness of the hydrological cycle, or the creation of a maintenance strategy, local expertise played a central role. The insights gained from local stakeholders, ranging from technical contributions to spiritual teachings about water and the forest, have been invaluable. As the project moves forward with future Cloud Chasers, it is clear that the success of the tower and its monitoring system will depend on continued engagement with the local team and the adaptability of the system to their needs.

9.2 Key recommendations

Improve planning and time management
Future teams should allocate sufficient time for design refinement, material sourcing, and construction to avoid delays. Clear, visual documentation and consistent communication with all stakeholders is a challenging task, but will ensure smoother execution.

Expand monitoring infrastructure for enhanced data collection
To capture more accurate atmospheric data, it is recommended to expand the tower to include above-canopy measurements. Additionally, expanding the set-up with, for example, a stemflow monitoring system, leaf wetness sensors, and increasing the depth of soil moisture sensors will provide a more comprehensive understanding of the canopy water balance.

Sensor calibration, maintenance, and placement
Careful calibration and placement of sensors are essential to ensure data accuracy and reliability. Although the current set-up in principle is installed according to the sensor manuals, trial and error is in practice the best way to find out if the complete set-up is functioning properly. Future teams should also implement more precise logging intervals where possible to capture rapid changes during short-term weather events.

Prioritise long-term sustainability and robust handover
For the tower's sustained success, future teams must prioritise robust maintenance plans and smooth handover. This includes establishing clear protocols that share all relevant construction details, maintenance procedures, and contextual knowledge with both local stakeholders and future researchers or Cloud Chasers. In a ten-week project, it is easy to get caught up in your own timeline and focus on meeting your team's direct goals. However, it is crucial to regularly step back and keep sight of the bigger picture and the overarching objectives of the project.

The importance of local knowledge and collaboration
As stressed many times, future teams should aim for a balance between technical optimisation and the cultural context of the region. Incorporating local knowledge into every phase of the project will help ensure its relevance, sustainability, and success.

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A Tower design sketches

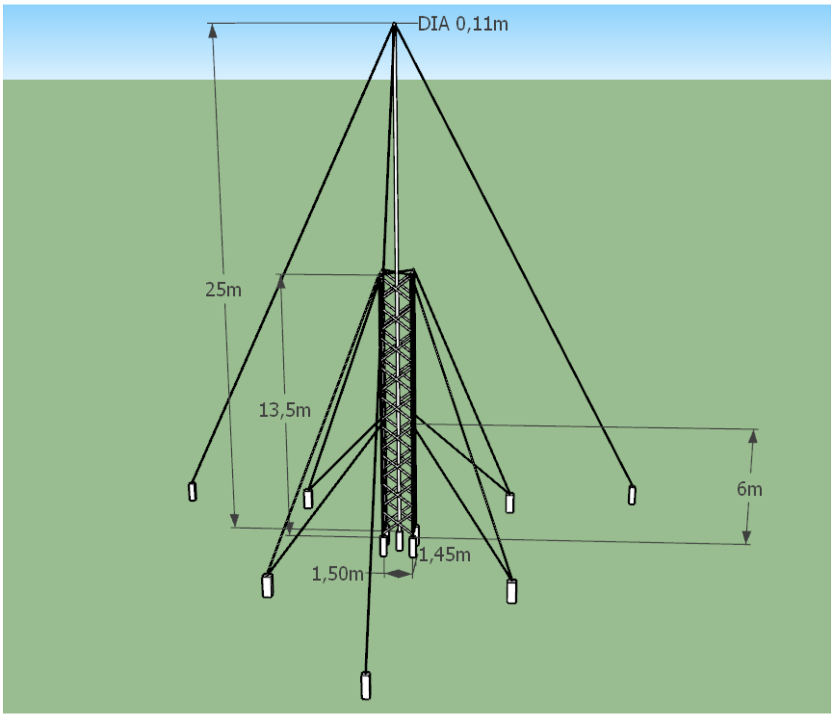


Figure 43: Overall design

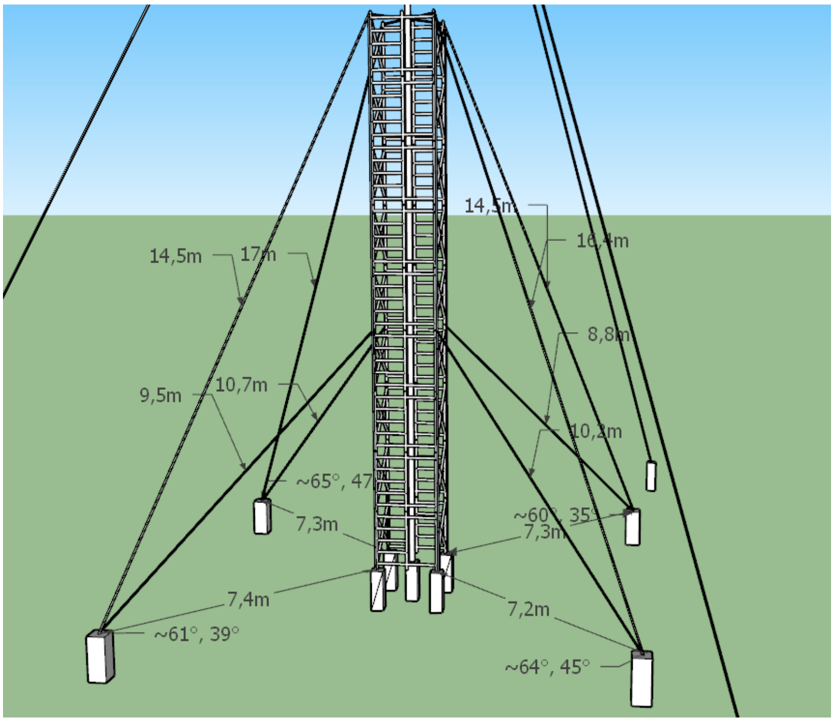


Figure 44: Tower guy wires

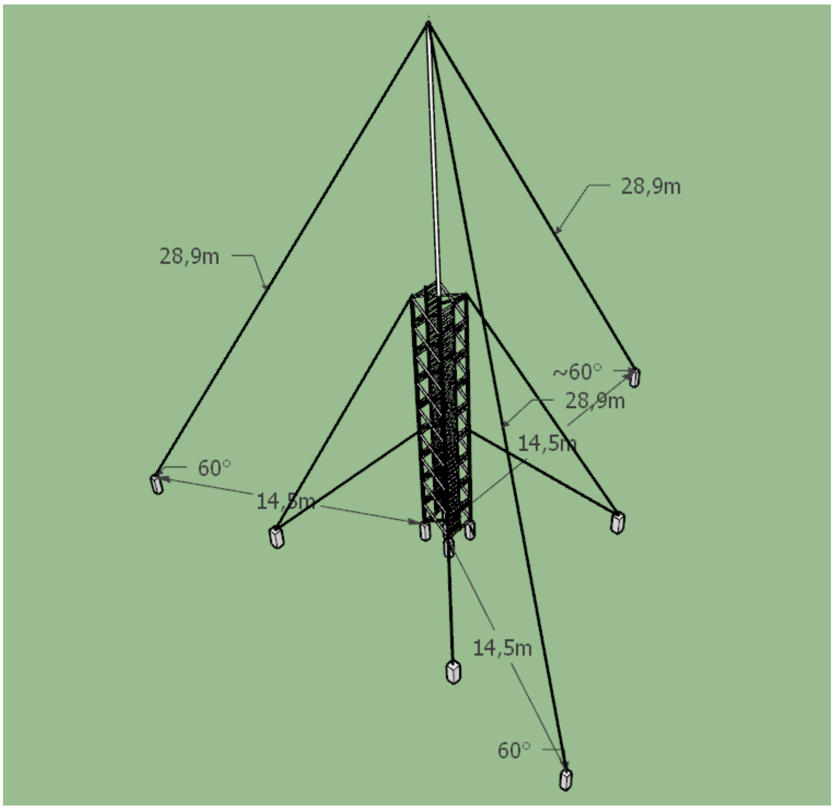


Figure 45: Pole guy wires

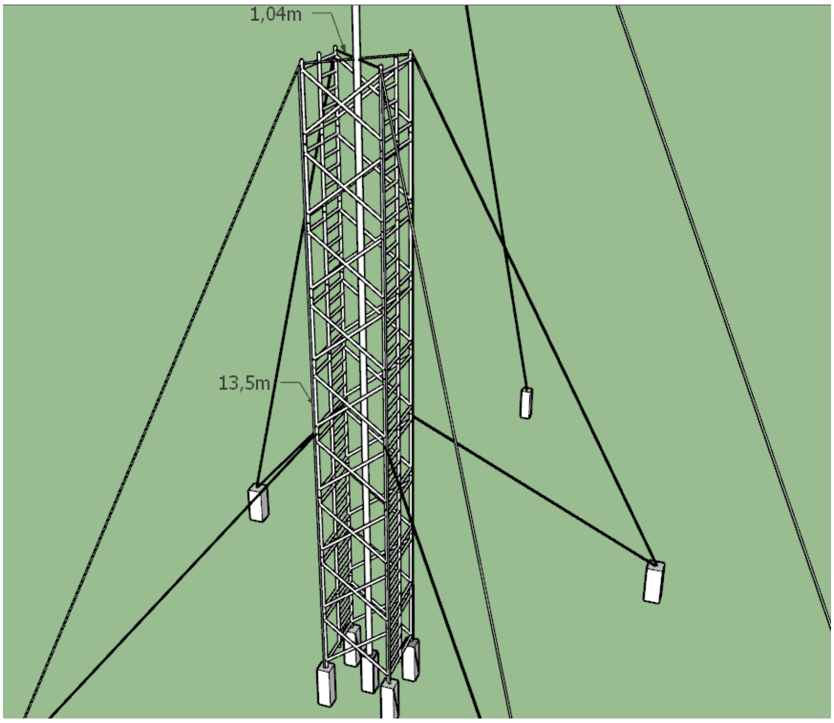


Figure 46: Guy wires along tower

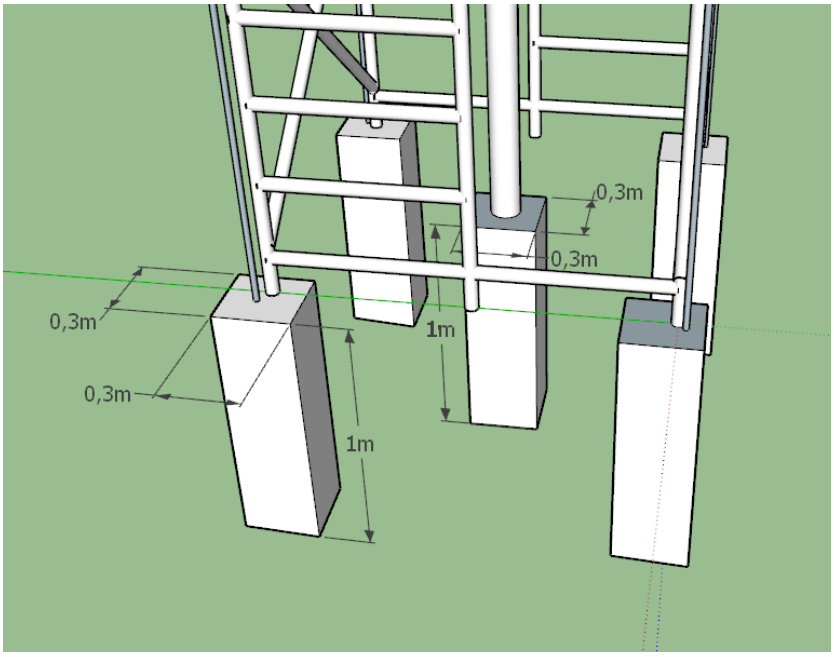


Figure 47: Foundation under tower and pole

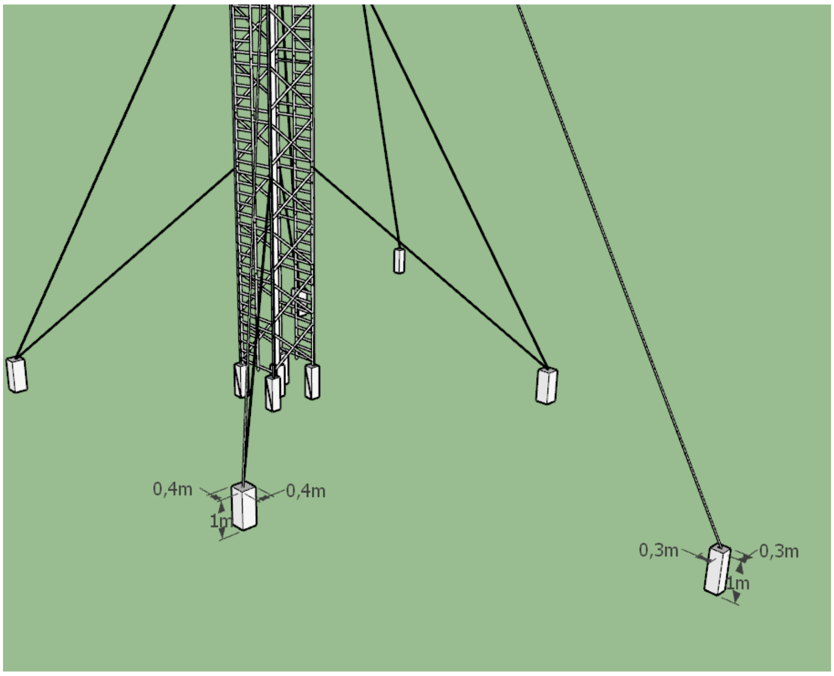


Figure 48: Foundation under guy wires

B Wind Load Scaffolding Tower Eurocode formulas

The complete Eurocode formulas for the wind load of a scaffolding tower (Nederlands Normalisatie Instituut 2011).

$$
\begin{aligned}
K_1 &= \frac{0.55A_f}{A_S} + \frac{0,8(A_c + A_{c,sup})}{A_S} \\
c_{f,s,0} &= c_{f,0,f} \cdot \frac{A_f}{A_S} + c_{f,0,c} \cdot \frac{A_c}{A_S} + c_{f,0,c,sup} \cdot \frac{A_{c,sup}}{A_S} \\
c_{f,0,f} &= 1.76C_1(1 - C_2\phi + \phi^2) \\
c_{f,0,c} &= C_1(1 - C_2\phi) + (C_1 + 0,875)\phi^2 \\
c_{f,0,c,sup} &= 1.9 - \sqrt{(1-\phi)(2.8 - 1.14C_1 + \phi)}
\end{aligned}
$$

Where:
θ = wind incidence angle [°]
A_f = projected area of flat-sided members [m^2]
A_c = projected area of circular members (subcritical) [m^2]
$A_{c,sup}$ = projected area of circular members (supercritical) [m^2]
A_S = total projected area of all members [m^2]
ϕ = solidity ratio [-]
C_1 = 2.25 (square), 1.9 (triangular) [-]
C_2 = 1.5 (square), 1.4 (triangular) [-]

C Field safety plan for the installation of monitoring equipment

Field safety plan for the installation of monitoring equipment

1. Introduction

This document outlines the safety protocol for the installation of the monitoring equipment on a 13,5-meter tower located in a cloud forest in Guatemala. Given the height of the structure, remote environmental conditions and technical complexity, adherence to this safety protocol is mandatory.

The installation encompasses the following components:

- 2 Rain gauges
- 1 Throughfall setup (including 1 rain gauge)
- 1 Wind sensor
- 2 Soil sensors
- 2 Solar radiation and relative humidity sensor
- 2 Fog traps
- 1 Solar panel
- 1 Data logger
- 1 Lightning protection system

2. Risk register

Risk description		Pre-response assessment		Risk response	Post-response assessment	
Risk event	Consequence	Probability	Impact		Probability	Impact
Fall from tower	Injury or fatality person falling and/or below	Medium	Severe	Reduce: use of PPE, fall arrest systems, trained personnel	Low	Moderate
Dropped tools or equipment	Injury or fatality to personnel below	Medium	Severe	Reduce: tool lanyards, tool belts, ground exclusion zone)	Low	Minor

Sudden weather changes/ lightning strike	Electrocution, equipment damage, work disruption	Moderate	High	Reduce: installation of lightning rod and ground wire, weather monitoring, suspend work during unsafe conditions	Medium	Minor
Trip hazards from equipment /wires	Minor to moderate injury	Medium	Moderate	Reduce: secure wires, tidy workspace, regular checks	Low	Minor

3. Safety protocol

Role allocation

Each team member is assigned a distinct, non-overlapping role to ensure safety and task clarity:

- Safety officer (on ground): Oversees all safety procedures, monitors climber safety, ensures compliance with protocols and maintains oversight in case of emergencies.
- First aid officer (on ground): Certified in first aid and CPR. This role must remain distinct from the Safety officer to ensure that in the event of an incident, medical attention can be provided while another individual continues to oversee overall safety.
- Climbers (3 individuals): Responsible for climbing and equipment installation. One climber is designated as the Climber-Communicator who maintains radio or verbal contact with the ground communicator.
- Ground communicator: Responsible for relaying messages clearly between climbers and other ground personnel and for status updates.

Personnel requirements

All personnel must wear the following PPE:

- Safety helmets
- Long-sleeved shirts and trousers
- Safety boots

All climbers must wear the following additional PPE:

- Full-body safety harnesses with dual lanyards

All climbers must be trained in:

- Working at heights
- Use of fall arrest systems
- Safe tool handling

The first aid officer must be certified in first aid and CPR.

Site and operation preparation

Prior to commencing the operation, the following steps must be completed in the specified order:

- Before ascending to the site:
    1. Plan the operation early in the day to avoid working during the warmest hours.
    2. Climatic conditions must be reviewed before each operation. Activities must cease during adverse weather, which is heavy rain, lightning, winds >30 km/h.
    3. Conduct a daily safety briefing to assign tasks and review emergency procedures. Make sure everyone feels well.
    4. Inspect all safety and installation equipment for damage or wear.
    5. Emergency communication devices must be tested and operational.
    6. Bring enough water and food for the duration of the operation to avoid dehydration and fatigue.
- When on site:
    7. Ensure tower guy wires are tensioned and anchored properly.
    8. Clearly mark and restrict the operational perimeter on the ground below the tower.

Safe climbing and work practices

When working at height, the following practices must be followed:

- Workers must be continuously attached to the tower with fall protection gear above 1 meter.
- The vertical distance between two individuals working directly above or below each other must be at least 5 meters.
- Establish wooden plank platforms securely before working at fixed points.
- Secure tools and devices with lanyards; never leave loose items on platforms.

Overall, the following practices must be followed:

- Do not walk on the prohibited area under the tower.
- Hydrate, eat and rest regularly to maintain energy and focus throughout the operation.

Installation procedures

For the installation of all components, the following procedures must be followed:

- Follow the pre-approved configuration plan for mounting sensors at designated heights (see sensor protocol).
- The lightning protection system must be installed before other equipment.

Communication plan

To maintain effective and coordinated communication during the operation, the following measures apply:

- Two walkie-talkies are used to ensure clear communication: one with the designated Climber-Communicator and one with the Ground Communicator.
- All communication between the tower and the ground must go through these two individuals for clarity.
- Climbers must provide a status update to the Ground Communicator every 10 minutes.
- Climbers must immediately report any risk, incident or unexpected condition.
- The Ground Communicator must have a mobile phone with reliable service coverage for emergency use.
- All communication should be clear, concise and relevant to safety or progress.

Environmental and wildlife protocols

Due to the conditions of the cloud forest environment, the following practices apply:

- Avoid contact with local fauna; do not disturb nests or habitats.
- Minimise vegetation disruption by following marked paths.
- Pack out all waste and leftover materials.

Emergency response plan

On-site kit must include:

- First aid supplies.
- Antiseptics and wound care.

In the event of an emergency, the following steps must be carried out in the specified order:

1. Cease operations.
2. Stabilise injured personnel if safe.
3. Notify emergency services and guide them to location.
4. Notify CCFC coordinators.

Post-installation safety review

The following checks must be completed post-installation:

- Perform an inspection of all mounted components and secured wiring.
- Test the data logger and sensors for proper functioning.
- Record any deviations from the planned installation and mitigation steps taken.
- Any violations or safety concerns must be documented and addressed immediately.

D Tower construction results

Figure 49: Tower bottom view

Figure 50: Tower side view

Figure 51: Throughfall setup

Figure 52: Throughfall setup

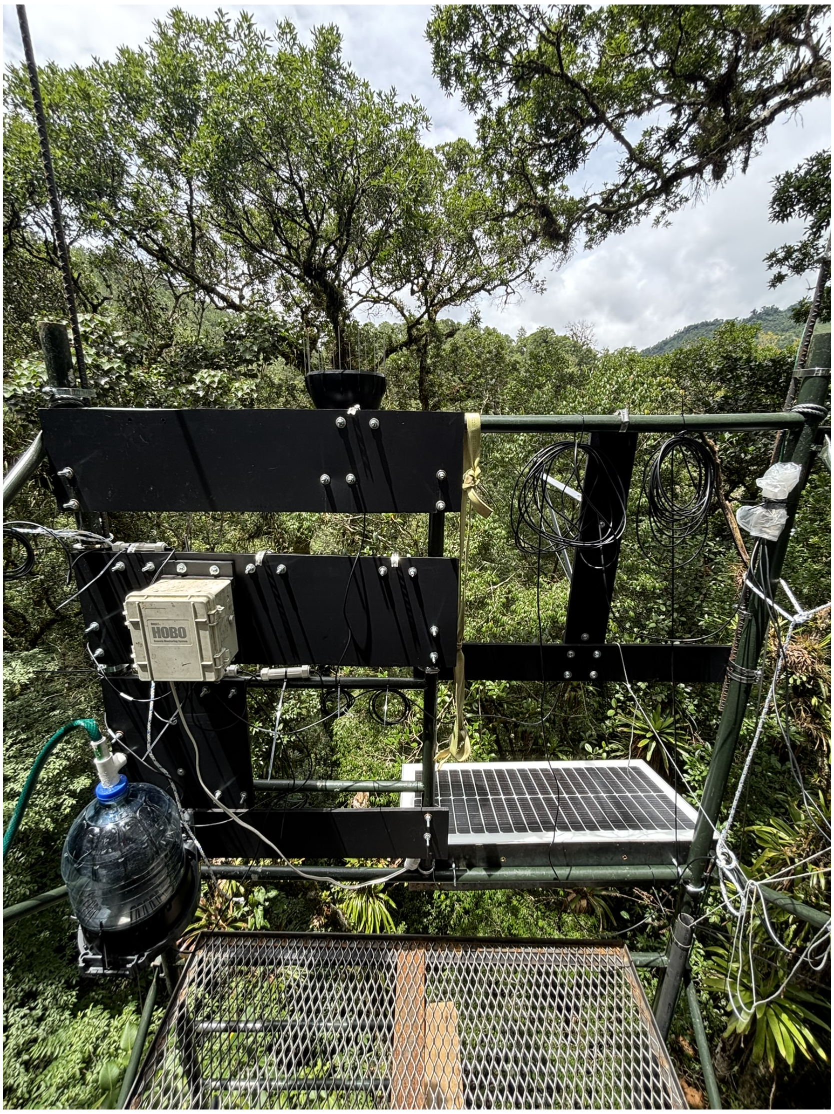


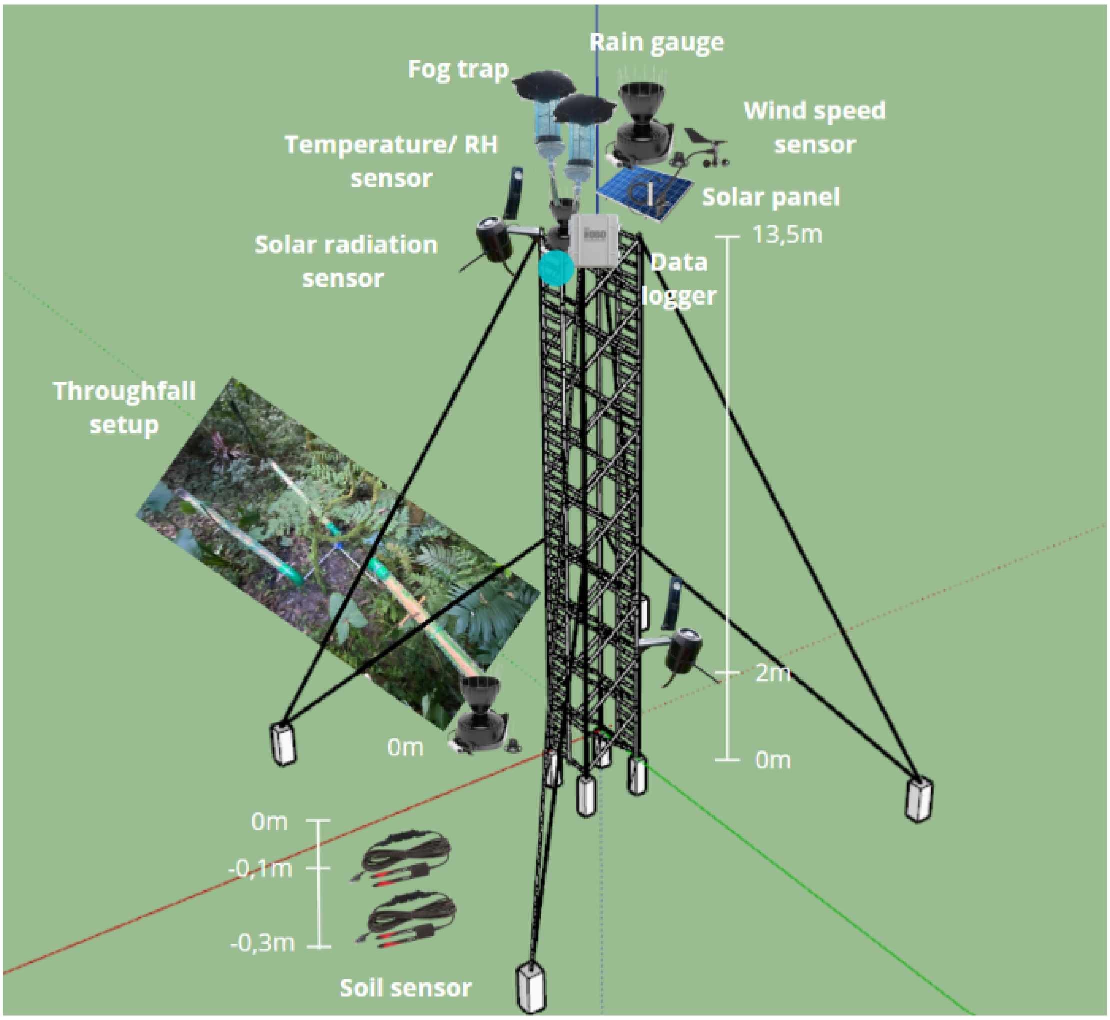
Figure 53: Solar panel and data logger setup

Figure 54: Solar sensor, RH/temperature and rain gauge setup

Figure 55: Fog trap setup

E Maintenance plan

E.1 Overview of components



E.2 Task overview

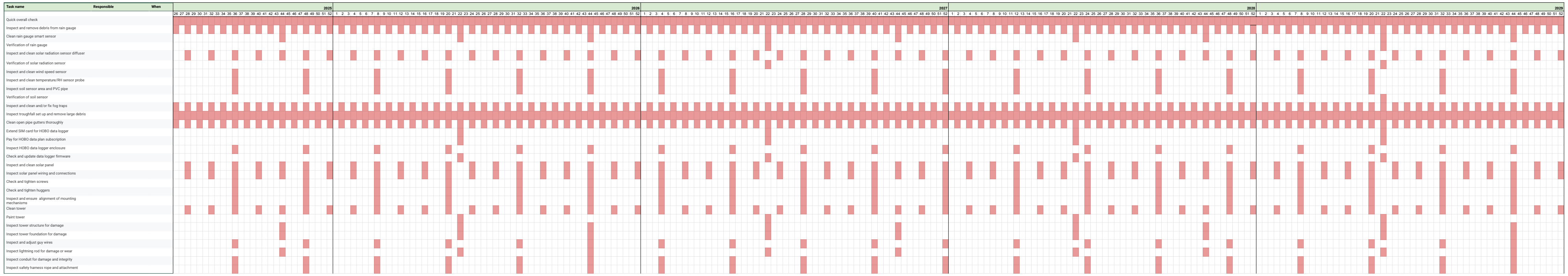
Category	Component	Task name	Task description	Estimated time	Frequency	Tools/materials
Sensor, Attachment, Tower	All	Quick overall check	Perform a quick overall visual inspection of the tower, sensors and attachments. Check for any obvious damage to the structure (e.g., bent metal, loose bolts), theft or tampering (e.g., missing components, vandalism). Check the guy wire tension, ensure the wires are taut and there are no signs of looseness or damage. Check for visible rust or wear on critical components, especially at the base and joints. Check for loose or damaged sensors and equipment. If any issues are found, report them immediately and take temporary measures to secure the tower until a more thorough inspection can be done.	15 minutes	Weekly	Binoculars (optional, for checking higher parts of the tower from a distance) Wrench or tool (optional, for tightening guy wires or securing components)
Sensor	Rain gauges	Inspect and remove debris from rain gauge	Inspect and remove any accumulated leaves, twigs, or other debris that may obstruct sensor function or drainage pathways	15 minutes	Biweekly	Soft brush Cloth or sponge Clean water (for rinsing if needed) Safety harness
Sensor	Rain gauges	Clean rain gauge smart sensor	Clean the smart sensor: 1. Detach the cone from the base. 2. Wipe the cone, screens, and tipping bucket with a soft damp cloth to remove pollen, dirt, and debris. 3. Use a pipe cleaner to clear the funnel hole and drain screens. 4. Rinse all parts with clean water. 5. Reassemble the cone and replace the screen securely.	30 minutes	Half yearly	Soft damp cloth Pipe cleaner:  Clean water Safety harness
Sensor	Rain gauges	Verification of rain gauge	The sensor operation can be tested by verifying that the number of tips results in the expected amount of rain logged in millimetres. This requires a one-minute logging interval and access to the station so that connection to HOBOlink can be made. To test the sensor operation: 1. Change the logging interval in HOBOlink to every minute and Save. 2. Press the Connect button on the station. 3. Press the Start button if the station is not logging. 4. Remove the cone from the base of the rain gauge by rotating the base until the latches on the cone line up with the latch openings in the base, then lifting the cone away from the base. 5. Slowly tip the spoon on the base until it drops and springs back, repeating 10 times in one minute. 6. Connect to HOBOlink so that the station can upload the latest rain data. 7. Export the data for the rain sensor. Ten tips should equate to 2 mm or 0.1 inch (depending on the model). Note that depending on where the tips occur within the logging interval, the data could be split across two logging intervals. If it is found that the data is missing tips, the manufacturer should be contacted for reparation or the rain gauge should be replaced.	45 minutes	Every two years or when noticing discrepancies or data loss	Computer with HOBOware or HOBOlink access Stopwatch or timer Log sheet or digital device for data recording
Sensor	Solar radiation sensors	Inspect and clean solar radiation sensor diffuser	Inspect the diffuser for dust or buildup. If dirty, gently wipe the diffuser with a damp sponge. Note: - Use only water or mild dish soap; never use alcohol, solvents, abrasives, or strong detergents. - Use vinegar if needed to remove hard water deposits. - Do not open the sensor (there are no user serviceable parts inside) or immerse it in liquid.	15 minutes	Monthly	Damp sponge or soft cloth Mild dish soap (optional) White vinegar (for hard water deposits) Clean water Safety harness

Category	Component	Task name	Task description	Estimated time	Frequency	Tools/materials
Sensor	Solar radiation sensors	Verification of solar radiation sensor	A basic verification can be performed using a calibrated light meter placed at the same orientation as the PAR sensor. Over a short recording period (e.g., 5 minutes with a 1-minute logging interval), average readings from both instruments can be compared. If needed, a calibration coefficient can be calculated by dividing the average light meter reading by the average PAR sensor reading. This coefficient can then be applied during post-processing (e.g., in Excel) to adjust the sensor values. If these tests pass, the sensor is working normally. If the readings are not comparible, it may be damaged, and the manufacturer should be contacted for reparation or the solar radiation sensor should be replaced.	30 minutes	Every two years or when noticing discrepancies or data loss	Calibrated light meter Computer with HOBOware and excel or data processing software Stopwatch or timer Measuring tape (optional, to ensure consistent sensor orientation)
Sensor	Wind speed sensor	Inspect and clean wind speed sensor	Inspect and gently clean the wind vane and cups if dirt or debris is visible. Do not immerse the sensor, apply lubricants, or use solvents.	15 minutes	Quarterly	Mild soap Soft cloth or sponge Clean water Safety harness
Sensor	Temperature/ relative humidity sensors	Inspect and clean temperature/RH sensor probe	Inspect the sensor probe and rinse it with distilled water to remove dust and contamination if dirty. Avoid using hot water, organic solvents, or detergents. Dry the probe before use.	15 minutes	Quarterly	Soft cloth or sponge Safety harness Distilled water Note: distilled water can be expensive. Filtered water or deionized water can be used as a more affordable alternative. The alternative should be free from minerals and impurities that could leave residues or affect sensor accuracy.
Sensor	Soil sensors	Inspect soil sensor area and PVC pipe	Inspect the ground around the soil sensor for any signs of erosion, landslides, or shifting that could affect sensor performance or stability. Also, check the PVC pipe that extends into the ground for any damage or shifting, ensuring that the sensor wires remain securely in place. If any erosion or damage is found, address the issue by stabilising the ground or securing the PVC pipe to prevent further displacement.	10 minutes	Quarterly or after severe weather events	Shovel (optional, for checking soil displacement)

Category	Component	Task name	Task description	Estimated time	Frequency	Tools/materials
Sensor	Soil sensors	Verification of soil sensor	To verify sensor performance over time, the following steps can be performed. These tests confirm that the sensor is functioning but do not assess measurement accuracy; for accuracy testing, refer to the soil calibration procedure described here: https://www.onsetcomp.com/resources/tech-notes/calibrating-ech2o-soil-moisture-sensors-application-note. 1. Remove the probe from the soil, do not pull it out of the soil by the cable. 2. Wash the probe with water and let it dry. 3. Plug the sensor into the logger. 4. Check the status of the device in HOBOware. If only HOBOlink is used, check the Latest Conditions for the device. Press the connect button on the HOBO station to upload the latest readings to HOBOlink if the connection interval is long. 5. Conduct an air or water test to check the actual readings against the expected readings. To conduct an air test, suspend the sensor by the cable so that it is hanging freely in the air and not near any objects. To conduct a distilled water test, suspend the probe in a room temperature container of fresh water. Make sure the container is large enough to completely cover the entire probe and that it does not touch the bottom or sides of the container. For both of these tests, it is important that the sensor's entire volume of influence is in air or water. For the volume of influence for the S-SMD-M005 probe, see: http://www.onsetcomp.com/support/tech-note/10hs-volume-sensitivity-application-note. 6. Compare the value in HOBOware or HOBOlink while running the test with the expected values below. The value should be within the specified range for the air or water test. Air should be between -0.48 to -0.13. Water should be between 0.46 to 0.70. If these tests pass, the sensor is working normally. Reinstall in the soil following the manual. If not, it may be damaged, and the manufacturer should be contacted for reparation or the soil sensor should be replaced.	60 minutes	Every four years or when noticing discrepancies or data loss	Shovel Clean water Soft cloth (for drying the sensor) Container large enough to fully submerge the probe in water Computer with HOBOware or HOBOlink access
Sensor	Fog traps	Inspect and clean and/or fix fog traps	Inspect all wires to ensure they are hanging straight and undamaged. Inspect the fishing line for any damage. Verify that all knots and connections are secure. Check the rebar where the fog trap is mounted to ensure it is stable and free from corrosion or damage. If any issues are found, re-align the wires, clean any debris, replace damaged components, or tighten connections as needed to maintain proper function.	10 minutes	Biweekly	Soft cloth or sponge Wire cutters (if replacing or adjusting wires) Replacement fishing line (if needed) Wrench or tool for tightening connections Safety harness
Sensor	Throughfall setup	Inspect troughfall set up and remove large debris	Remove any leaves, twigs, or debris from the rain gauge and clear large objects on the outer chicken wire of the open pipe gutters that may obstruct rain collection. Also, inspect the wooden holders to ensure they are intact and holding the pipes in place.	10 minutes	Weekly	Soft brush or cloth
Sensor	Throughfall setup	Clean open pipe gutters thoroughly	Clean the open pipe gutters by either removing the elbow and filter to clean them thoroughly or, alternatively, detach the open pipe gutters from the elbow and inverting it to remove debris.	15 minutes	Biweekly	Soft brush or cloth Mild soap or water (for cleaning) Wrench or tool for detaching parts
Sensor	HOBO datalogger	Extend SIM card for HOBO data logger	Check the expiration date of the SIM card subscription for the HOBO data logger, and extend or renew the subscription as needed to ensure continuous data transmission.	15 minutes	Annually or as per subscription renewal date	Computer SIM card details (account info, renewal options)
Sensor	HOBO datalogger	Pay for HOBO data plan subscription	Verify the expiration date of the HOBO cloud data plan subscription and ensure timely renewal to maintain continuous data logging and cloud access. If the subscription is near expiration, renew the plan through the provider's website or customer service.	15 minutes	Annually or as per subscription renewal date	Computer Account details for HOBO cloud service
Sensor	HOBO datalogger	Inspect HOBO data logger enclosure	Inspect the protective enclosure of the HOBO data logger for any signs of damage, cracks, or water ingress. If the enclosure is damaged, replace it to protect the logger from environmental factors.	5 minutes	Quarterly or after severe weather events	Safety harness Replacement enclosure (if needed

Category	Component	Task name	Task description	Estimated time	Frequency	Tools/materials
Sensor	HOBO datalogger	Check and update data logger firmware	Ensure that the firmware of the HOBO data logger is up-to-date to ensure optimal performance and compatibility with other systems. If a firmware update is available, follow the manufacturer's instructions to update the firmware.	15 minutes	Annually	Computer with HOBOware or HOBOlink
Sensor	Solar panel	Inspect and clean solar panel	Inspect the solar panel for any dirt, dust, or debris that may obstruct sunlight, and clean the surface using a soft cloth.	15 minutes	Monthly or after severe weather events	Soft cloth or sponge Mild soap or water Safety harness
Sensor	Solar panel	Inspect solar panel wiring and connections	Inspect the wiring connected to the solar panel for any signs of wear or loose connections. Ensure all connections are secure and free of corrosion. If any issues are found, repair or replace damaged wires and secure any loose connections to ensure optimal performance.	10 minutes	Monthly or after severe weather events	Wrench or tool for tightening connections Safety harness Wire cutters/strippers (if needed)
Attachment	Screws	Check and tighten screws	Check if all screws (including solar panel arm) are properly tightened and ensure none are rusted or showing signs of corrosion. If any screws are loose or rusted, tighten or replace them.	30 minutes	Quarterly or after severe weather events	Wrench and screwdriver Replacement screws Safety harness
Attachment	Huggers	Check and tighten huggers	Check if all huggers on the tower are properly tightened. If any huggers are found to be loose, tighten them immediately.	30 minutes	Quarterly or after severe weather events	Safety harness Wrench or tool for adjustments
Attachment	Sensor mounting mechanisms	Inspect and ensure alignment of mounting mechanisms	Inspect the mounting mechanisms for any signs of cracks, damage, or misalignment, and ensure they are securely positioned and level. If any issues are found, repair or replace the damaged components and realign or adjust the mechanisms as necessary to ensure proper sensor positioning.	20 minutes	Quarterly or after severe weather events	Level (for checking alignment) Safety harness Wrench or tool for adjustments
Tower	Scaffolding	Clean tower	Visually inspect the tower structure for plant growth and clean the tower by removing any moss, algae, or vegetation when needed.	15-30 minutes	Monthly	Soft cloth or brush Mild soap or water Pruning shears Safety harness
Tower	Scaffolding	Paint tower	Apply a fresh coat of corrosive-resistant paint to protect from deterioration. Ensure to clean the affected areas before painting for better adhesion.	2x 6 hours	Annualy	Corrosive-resistant paint Paintbrush or roller Drop cloth or tarp Safety harness
Tower	Scaffolding	Inspect tower structure for damage	Visually inspect the tower structure for any signs of rust, cracks, or damage to metal components, and ensure stability. If issues are found, schedule repairs or apply protective coatings to prevent further deterioration.	30 minutes	Half yearly or after severe weather events	Safety harness Rust-resistant paint (if required for repairs)
Tower	Foundation	Inspect tower foundation for damage	Visually check the foundation for signs of cracking, settling, or water accumulation that could affect the tower's stability. If any problems are found, reinforce the foundation or address drainage issues immediately.	15 minutes	Half yearly or after severe weather events	Shovel (optional, for checking foundation integrity) Measuring tape (optional, for checking settlement)
Tower	Guy wires	Inspect and adjust guy wires	Inspect the guy wires for proper tension and security, and check the attachment points for any signs of wear or damage. If the tension is inadequate or damage is found, tighten or replace the guy wires as needed to ensure stability.	30 minutes	Quarterly or after severe weather events	Wrench or tool for tightening Safety harness Replacement guy wires (if needed)
Tower	Lightning rod	Inspect lightning rod for damage or wear	Inspect the lightning rod, copper wire, and grounding pole for any signs of corrosion, damage, or wear. Remove any dirt, corrosion, or other debris that could reduce conductivity. Ensure the copper wire is securely attached and the metal pole remains firmly in the ground. Ensure the metal pole is at least 30 cm deep in the ground, as required for effective grounding. If any corrosion or damage is found, clean the affected areas and replace damaged components to maintain functionality.	10 minutes	Half yearly or after severe weather events	Soft cloth Mild soap Replacement parts (copper wire, grounding pole, etc. if needed) Wrench or tool for tightening attachments Shovel or digging tool (if adjustments are needed) Measuring tape (optional, for checking depth) Safety harness
Tower	Conduits	Inspect conduit for damage and integrity	Visually inspect the conduit for any holes, cracks, or signs of wear. Ensure that it is properly sealed and waterproof. Check the junctions and connectors for secure fittings and potential damage. If any issues are found, repair or replace the affected sections of the conduit to maintain water-tight integrity.	20 minutes	Quarterly	Safety harness Waterproof sealant or tape (if repairs are needed) Replacement conduit (if necessary) Wrench or tool for securing connectors
Tower	Safety harness rope	Inspect safety harness rope and attachment	Inspect the rope used for securing the safety harness for any signs of wear or damage. Check the knots and the connection points where the rope attaches to the tower to ensure they are secure and in good condition. If any damage or looseness is found, replace the rope, re-tie the knots, or re-secure the connections as necessary.	20 minutes	Quarterly	Replacement rope (if necessary) Safety harness

E.3 Planning


Task name
Responsible
When
2025
2026
2027
2028
2029
26 27 28 29 30 31 32 33 34 35 36 37 38 39 40 41 42 43 44 45 46 47 48 49 50 51 52
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31 32 33 34 35 36 37 38 39 40 41 42 43 44 45 46 47 48 49 50 51 52
Quick overall check
Inspect and remove debris from rain gauge
Clean rain gauge smart sensor
Verification of rain gauge
Inspect and clean solar radiation sensor diffuser
Verification of solar radiation sensor
Inspect and clean wind speed sensor
Inspect and clean temperature/RH sensor probe
Inspect soil sensor area and PVC pipe
Verification of soil sensor
Inspect and clean and/or fix fog traps
Inspect troughfall set up and remove large debris
Clean open pipe gutters thoroughly
Extend SIM card for HOBO data logger
Pay for HOBO data plan subscription
Inspect HOBO data logger enclosure
Check and update data logger firmware
Inspect and clean solar panel
Inspect solar panel wiring and connections
Check and tighten screws
Check and tighten huggers
Inspect and ensure alignment of mounting mechanisms
Clean tower
Paint tower
Inspect tower structure for damage
Inspect tower foundation for damage
Inspect and adjust guy wires
Inspect lightning rod for damage or wear
Inspect conduit for damage and integrity
Inspect safety harness rope and attachment

E.4 Checklist

Filtered on weekly, bi-weekly and monthly maintenance.

General information	
Date of inspection:	
Inspected by:	
Condition notes	
Any general comments or observations about the tower's condition:	
Identified issues, damage, or abnormalities found during the inspection:	
Immediate actions taken during the inspection or repair:	
Any parts that were replaced or serviced:	

Frequency	Task name	Completed	Comments / findings	Action required
Weekly	Quick overall check	☐		
Weekly	Inspect troughfall set up and remove large debris	☐		
Biweekly	Inspect and remove debris from rain gauge	☐		
Biweekly	Inspect and clean and/or fix fog traps	☐		
Biweekly	Clean open pipe gutters thoroughly	☐		
Monthly	Inspect and clean solar radiation sensor diffuser	☐		
Monthly	Inspect and clean solar panel	☐		
Monthly	Inspect solar panel wiring and connections	☐		
Monthly	Clean tower	☐		

F Sensor set-up

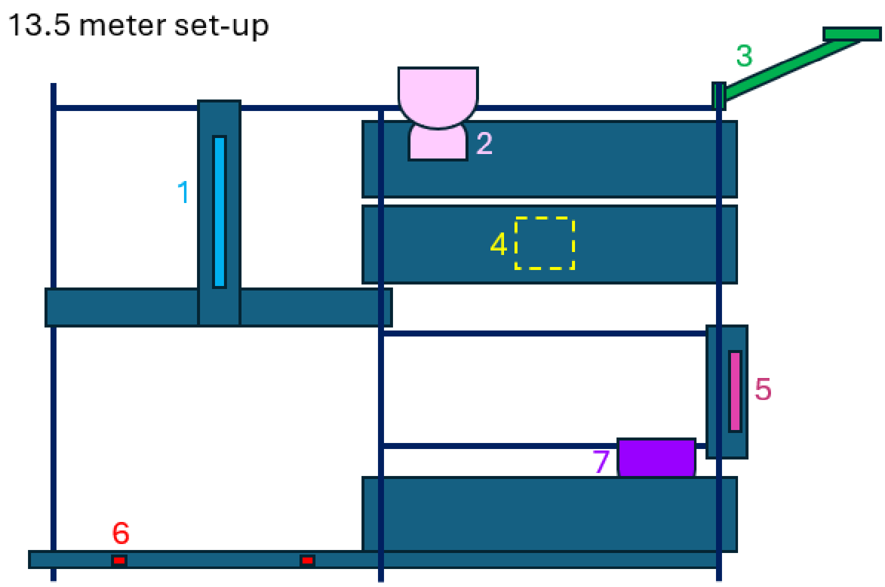


Figure 56: 13.5 meter set-up

1. Solar Radiation sensor
2. Rain Gauge (vertical precipitation)
3. Wind Speed and Direction sensor
4. HOBO data logger
5. Temperature / Relative Humidity sensor
6. Solar Panel
7. Rain Gauge (fog traps)

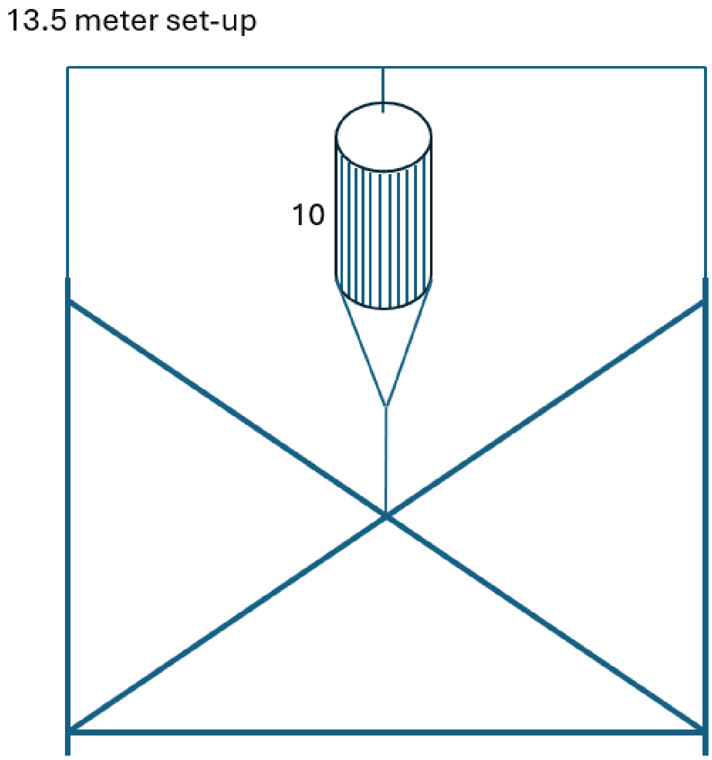


Figure 57: 13.5 meter fog trap set-up

10. Fog Trap (also 1 installed on the other side of the tower, at 13.5 meter)

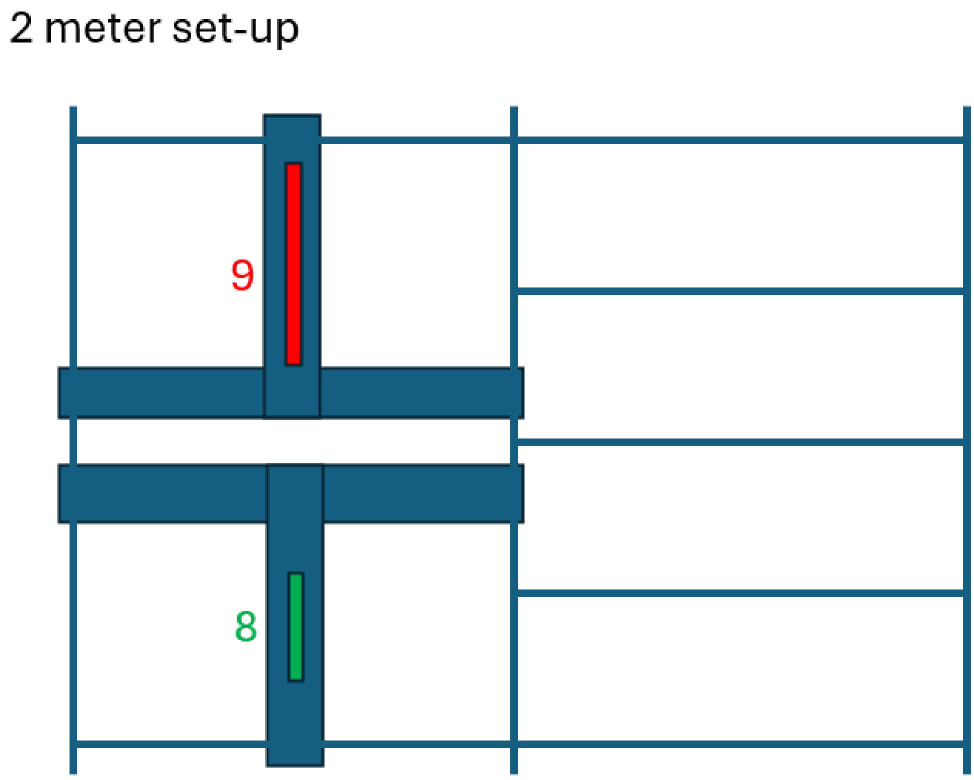


Figure 58: 2 meter set-up

8. Solar Radiation sensor
9. Temperature / Relative Humidity sensor

G Clicking mechanisms with sensor

(a) Rain gauge (Vertical precipitation)

(b) Rain gauge (Throughfall)

(c) Solar radiation sensor

(d) Temperature / Relative humidity sensor

(e) HOBO data logger

Figure 59: Clicking mechanisms with sensor