A Study into Cloud Forests

The installation of a long-term setup to investigate the impact of a cloud forest canopy on the Mestelá River catchment and its effect on various stakeholders

CEGM3000: Multidisciplinary Project

Cloud Chasers II

Delft University of Technology

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by

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Abstract

The research question addressed in this study is *"To what extent does the presence of a cloud forest canopy impact the Mestelá River catchment and how will this affect the various involved stakeholders?"*. The study aims to investigate the importance of cloud forests in the Mestelá River catchment, Alta Verapaz, Guatemala, related to water security and the social impact of cloud forest conservation and management. The research methods used in this study were a combination of quantitative and qualitative methods.

Cloud forests play a vital role in regulating water flow in catchments. The Mestelá River catchment, where the NGO Community Cloud Forest Conservation (CCFC) is situated, is the focus of this research. The project's primary aim was to establish a long-term canopy setup, ensuring future data collection. The project's scope encompasses a range of methodologies, including the installation of a long-term measurement station in the canopy, computation of the Mestelá River discharge, the development of a rating curve, and the utilisation of a FLEX-Topo model to simulate the hydrological cycle in the catchment. Additionally, a stakeholder management analysis was conducted to understand the complex impact of cloud forests (conservation) on various stakeholders.

The study did not explicitly formulate any hypotheses, but the findings provide evidence for the impact of cloud forest canopies on river catchments and discharge. The study also has limitations, including the small sample size and the lack of long-term data. However, the study provides valuable insights into the importance of cloud forest ecosystems for water security and the social impact of cloud forest conservation and management. The stakeholder analysis reveals that for CCFC two methods of advocacy can be used. Whilst the CCFC is effective in bottom-up engagement with the community, in addition, a strip for small children was constructed. For top-down advocacy, using the FLEX-Topo model for visualising water security in combination with cloud forest protection holds promise.

The implications of this work are substantial for cloud forest conservation and associated ecosystems. The findings offer valuable insights for developing effective conservation strategies that consider the canopy's impact on the catchment and its stakeholders. It is important to note that the FLEX-Topo model is currently conceptual and requires further refinement and detail for the Mestelá River catchment. Nevertheless, this study contributes significantly to the understanding of cloud forest ecosystems and offers practical and theoretical applications for future research and conservation efforts.

Contents

Nomenclature

Abbreviations

Table 1: Abbreviations and Definitions

Abbreviation	Definition
CCFC	Community Cloud Forest Conservation
COCODE	Consejo Comunitario de Desarrollo
CONAP	Consejo Nacional de Areas Protegidas
DEM	Digital Elevation Model
EDM	Electronic Distance Measurement
GTM	Guatemala Transverse Mercator
HAND	Height Above Nearest Drainage
HBV	Hydrologiska Byråns Vattenbalansavdelning
INAB	Instituto Nacional de Bosques
LAI	Leaf Area Index
LDD	Local Drain Direction
MDP	Multidisciplinary project
NDVI	Normalised Difference Vegetation Index
NDWI	Normalised Difference Water Index
NGO	Non-Governmental Organisation
NSE	Nash-Sutcliffe Efficiency
TMCF	Tropical Montane Cloud Forest
WGS	World Geodetic System

1 Introduction

1.1. Introduction

This multidisciplinary project (MDP) is situated in Alta Verapaz, Guatemala, a region with various Mayan communities. One of the largest Mayan communities in Alta Verapaz is the Q'eqchi' community, with more than 1,300,000 individuals who mainly speak the Q'eqchi' language [28, 76]. The study area is focused on the Mestelá River catchment, which serves as an important water source for the city of Cobán, see Figure 1.1. A substantial part of the local population, particularly the Q'eqchi'-speaking community, relies on the Mestelá River for their essential water needs, which encompasses drinking and household purposes. Our project is conducted on behalf of the Community Cloud Forest Conservation (CCFC), a non-governmental organisation dedicated to community education and the preservation of cloud forests. Cloud forests are essential for base water flow and peak attenuation, acting as natural reservoirs by capturing, storing, and slowly releasing water. Tropical montane cloud forests are unique ecosystems with a unique hydrological characteristic: persistent fog influx. In this project, we explore the critical role of cloud forests in sustaining downstream water resources, with a primary focus on their significance for ensuring water security in the Mestelá River catchment.

Figure 1.1: Mestelá River ends up in the Cahabón River, being one of the main water resources for the city of Cobán. In this picture, the Mestelá catchment represents the upstream area from the CCFC. In reality, the catchment is larger. The city of Cobán lies north of the water extraction point.

1.2. Relevance

One of the key challenges facing the region is the poverty of the community. Therefore, concerns such as deforestation, polluted rivers and climate change are not preoccupying the community around the Cahabón River. Next to that, the low water security of the Cahabón River results in large socio-economical impacts. Droughts and floods often damage the area, as can be seen in Figure 1.2. Moreover, the Mestelá River, which is a significant tributary of the upper Cahabón River, serves as an important water source for the city of Cobán. A substantial part of the local population relies on the Mestelá River for their essential water needs, which encompasses drinking and household purposes. By understanding the hydrological cycle of the Mestelá River catchment, and showing the importance of cloud forests, it is possible to characterise the water security of the Cahabón River. With this information, tackling problems such as deforestation and pollution is made possible. By constructing a stakeholder framework, CCFC is further supported to carry out our conclusions to the local community.

Figure 1.2: Flooding in Alta Verapaz in November 2020 [2].

1.3. Scope and Objectives of the Project

The scope of this MDP includes the following components: acquiring hydrological information about the canopy and the Mestelá River, developing a hydrological model and setting up a stakeholder framework. These topics will be elaborated upon and constitute the project's primary objectives. The project's broader vision is to lay the foundation for a long-term research initiative, with the current objectives serving as the initial phase.

1.3.1. Rainfall-Runoff Processes

A good understanding of rainfall-runoff processes within a cloud forest is essential for effectively modelling these phenomena and providing accurate information to stakeholders. These rainfall-runoff processes are special in cloud forests due to their ability to capture a significant amount of fog, resulting in not only traditional vertical precipitation but also horizontal precipitation processes. To gain more insight into these processes, we break down this objective into two sub-goals. The first is to explain the dynamics within the forest canopy and the second one is to grasp the hydrological workings of the Mestelá River. Once both components are fully understood, they can be combined to get a better understanding of the rainfall-runoff processes in a cloud forest.

Canopy Monitoring

The project entails the collection of hydrological data via a self-constructed long-term setup to be deployed within the Mestelá River catchment. This inspiration for this long-term setup is derived from the temporary setup built by Cloud Chasers I. While certain components of their temporary setup will be retained and enhanced, supplementary sensors will be added to the setup [1]. A detailed exploration of these modifications is provided in Section 3.3. Moreover, careful site selection is necessary due to the substantial costs of the equipment, as detailed in Section 3.2.

Mestelá River Hydrology

Scarce data exists concerning the characteristics of the Mestelá River such as water depth and discharge. This scarcity arises from the absence of water level gauges in the immediate surroundings and the lack of historical flood data. Consequently, addressing this lack of information constitutes a secondary objective: to establish a basic understanding of the Mestelá River's hydrology by quantifying water depth and discharge by creating a rating curve. Understanding this regard will enable the development of a model by integrating this information with the canopy monitoring data. Further elaboration on this objective will be provided in Sections 3.4 and 3.5.

1.3.2. Stakeholder Management

The second main objective is to develop a framework for effective stakeholder management tailored for the use by CCFC, utilising insights gathered through interviews and a comprehensive analysis of challenges faced and strategies currently employed. This research aims to bridge the gap between stakeholder needs and the practices of CCFC, ensuring alignment with the concerns and needs expressed by stakeholders involved in or affected by the cloud forest ecosystem.

To accomplish this an exploration and analysis of the challenges is performed. This includes an understanding of the strategies currently employed by these stakeholders. To achieve this, qualitative interviews will be conducted with a diverse group of stakeholders and other relevant actors, facilitating an in-depth examination of challenges, issues, and perspectives. Subsequently, collected data will undergo story analysis to uncover common themes, patterns, and interdependencies, resulting in a comprehensive overview of challenges and potential strategies. This analysis will serve as the basis for constructing the stakeholder management framework.

This comprehensive and broad exploration of challenges ensures that CCFC's stakeholder management practices align with stakeholder and broader community concerns and needs, taking into account the unique context and objectives of the organisation. Ultimately, the research seeks to implement one of these stakeholder management strategies in collaboration with CCFC, translating research findings into practical actions.

1.4. Research Question

The research question which is accompanied by these objectives is defined as follows:

"To what extent does the presence of a cloud forest canopy impact the Mestelá River catchment and how will this affect the various involved stakeholders?".

The research question is divided into three sub-questions:

1. *How should a long-term measurement station be established to monitor hydrological processes within the cloud forest canopy?*
   This question will be answered in Sections 2.3 and 3.2. The data resulting from the long-term measurement station will be discussed in Sections 4.1 and 4.3.
2. *How should a hydrological model be developed to clarify the relationship between cloud forests and the water security of the Mestelá River?*
   The answer to this question will be elaborated on in Sections 3.4 and 3.5. The results will be shown in Sections 4.4, 4.5 and 4.6.

3. *How can the socio-ecological impact of CCFC be enhanced through effective stakeholder management?*
   In Section 3.6 the methodology of answering this question is explained. The resulting stakeholder management framework will be presented in Section 4.7.

1.5. Structure of the Report

This report will first provide background information and delve into previous research, which can be found in Chapter 2. Also, the basic principles of the research will be elaborated on, such as the importance of cloud forests (Section 2.2), the hydrological processes at the canopy (Section 2.3), as well as an introduction to two types of hydrological models (Section 2.4) and stakeholder management (Section 2.6).

Chapter 3 consists of the substantial part of the report. First, the Mestelá River catchment is classified using GIS and satellite imagery (Section 3.1). Following this, the construction of the long-term measurement station is explained (3.2) and how the fluxes and states are measured (Section 3.3). Next, in Section 3.4, the computation of the Mestelá River discharge is explained. In Section 3.5, all information from the previous sections will come together as influxes and ouflux for the FLEX-Topo model. Finally, in Section 3.6, the execution of the stakeholder management analysis is elaborated on.

The results of this study will be presented in Chapter 4. Another important chapter is related to the discussion (Chapter 5), where the limits and assumptions of the research are explained extensively. Finally, a conclusion will be drawn in Chapter 6 and recommendations for further research are explained in 7.

2

Literature Review

2.1. The Role of CCFC and the Challenges of Cloud Forests

2.1.1. The Socioeconomic Struggle of Cloud Forests in Alta Verapaz

Alta Verapaz, Guatemala, is marked by extreme poverty. The region's poor socioeconomic conditions are linked to numerous environmental problems and social disparities; such as lack of access to education [94].

The cloud forests in Alta Verapaz play a vital role in providing water resources for local communities and agriculture. The rivers and streams originating in these forests serve as essential sources of drinking water and irrigation. Additionally, these ecosystems act as natural regulators of water quality and quantity and reduce erosion [84]. Despite their significance, cloud forests in Alta Verapaz face severe threats, including (illegal) land use changes and climate change. The main reason for land use changes is deforestation for the expansion of livestock, and the expansion of agricultural land for the production of basic grains and wood production. The major incentives to change land use are: the low relative profitability of forests, food security, and the need for direct gains and benefits for the survival of poor small producers [99]. A significant concern revolves around the rapid transformation of cloud forests into agricultural areas, driven by the increasing demand for farmland due to the exponential population growth in this region. [81]. This deforestation is reducing the ecosystem's capacity to regulate the water cycle and resulting in habitat loss. This results in increased runoff, erosion, and floods, negatively impacting water quality and availability [68].

2.1.2. Community Cloud Forest Conservation

CCFC's work is concentrated within the villages bordering the cloud forests of the Sierra Yalijux, Sierra Caquipec, Sierra Xucaneb, and Sierra Sacranix in the central highlands of Guatemala. CCFC's mission centres around holistic community-based approaches to conserve cloud forests while addressing pressing issues of poverty, education, and social development.

CCFC's mission is underpinned by a vision that stands on two pillars: the socio and ecological dimensions. This dual focus recognises the intimate relationship between social well-being and ecological conservation, a perspective that is fundamental to their approach. The goal is not only to save cloud forests but also to enhance the quality of life for local inhabitants, thus addressing both social and environmental challenges. CCFC acknowledges the connection between poverty and environmental degradation. Therefore CCFC's mission is seen as a holistic community-based approach to cloud forest conservation.

The primary threat to the survival of cloud forests in this region is the expansion of agriculture within the mountain villages. The remote, rural nature of these villages underscores the importance of CCFC's community-based approach in addressing the unique challenges posed by their social and geographic context. Within this context, the social factors encompass widespread poverty, a rapidly growing population, Mayan culture, and educational deficiencies. On the geographical front, the challenges are intricately tied to the mountainous ecosystem. These villages are not only located adjacent to cloud forests but also face obstacles associated with limited accessibility and their upstream position, which means that activities upstream can significantly impact downstream regions.

CCFC's initiatives span the fields of education, reforestation, ecotourism and agriculture. Each of these areas receives targeted projects aimed at maximising conservation impact, alleviating poverty, enhancing nutrition, increasing family incomes, and fostering community and individual development. By integrating education, conservation, and socio-economic development, CCFC addresses not only the challenges of deforestation and biodiversity loss but also the interconnected issues of poverty and lack of education [18].

2.2. Cloud Forests and Water Security in Alta Verapaz

In this section, the role of cloud forests is elaborated alongside the challenges they face within the department of Alta Verapaz.

2.2.1. Characteristics of a Cloud Forest

The main principles of a Tropical Montane Cloud Forest (TMCF) will be introduced in this section. The most important distinction between cloud forests and other (tropical) forests is the ability to intercept fog, also called horizontal precipitation. Fog interception is observed when a cloud passes through a forest canopy, causing moisture to condense on the leaves and other vegetation [41]. Cloud passing can exclusively take place at specific elevations. In Central America, fog interception is common between the elevation of 840 m and 3475 m [55]. The amount of fog intercepted by a cloud forest is determined by various local variables, including canopy height, canopy structure, wind speed, leaf surface area, slope orientation, as well as the orientation of leaves and branches [41]. TMCFs are generally divided into two classes, lower montane cloud forest and upper montane cloud forest. The distinction between the two is the level of persistent cloud condensation. The moisture content and temperature of the atmosphere influence the lower elevation of cloud formation, and the more humid the uplifted air is, the quicker it will condense [11].

The cloud forest's property of intercepting fog provides the ability to extract water during periods of no precipitation. These storage characteristics lead to increased base flow in streams and water level fluctuations being dampened. Next to that, there are more general ecosystem services that forests provide such as preventing soil erosion and sedimentation of the river.

2.2.2. Water Security in Alta Verapaz

Alta Verapaz features a karst topography, characterised by its gradual formation through the erosion of soluble carbonate rock layers like limestone. In such areas, it is typical for little surface water to be present, resulting in limited storage capacity. This leads to rivers responding quickly with significant fluctuations in water depth. In combination with the climate of the Alta Verapaz region, where it is common to have high humidity and heavy rainfall, this results in even larger fluctuations in the water level. Thus, the river overflows during floods, carrying along debris from the riverbeds and contributing to increased river pollution. Conversely, during periods of low precipitation, droughts become a concern.

In Sierra Yalijux, the mountain range where the Mestelá River catchment is situated, the cloud forest cover decreased by 17.7% between 1986 and 2006 [75]. The main reason for deforestation is to expand agricultural land, which is even more increased due to population growth. Other reasons are logging for firewood and the subdivision of land [75]. The deforestation of a cloud forest results in reduced fog interception during the dry season, leading to a decline in base flow. Additionally, it reduces the attenuation in a catchment [9].

2.3. Canopy Monitoring

In order to monitor the canopy and collect input data for the model, it is essential to understand the most critical processes in the hydrological balance. Afterwards, in Chapter 3 the different devices to measure the meteorological conditions and components are discussed.

2.3.1. Hydrological Balance of the Canopy

Conceptual hydrological models serve as simplified representations of hydrological processes occurring within a specific catchment. Their primary purpose is to refine complex interactions into key elements, facilitating a conceptual grasp of the movement of water through the system [58]. Within this framework, the canopy is the first interface between atmospheric and terrestrial water. Therefore, it becomes essential to acquire a good understanding of the hydrological balance of the canopy.

This hydrological balance encompasses three fundamental components: influx, states, and outflux, each of which further subdivides into distinct hydrological processes. For the influx, we delineate between vertical precipitation and horizontal precipitation. The states consists of interception storage, unsaturated soil storage, saturated soil storage and fast (overland) flow. Finally, the outflux is governed by throughfall, stemflow and evaporation processes [22].

2.3.2. Canopy Influx

Precipitation is the primary driver of the influx component in a hydrological balance. Its nature varies across different climates, thereby influencing the hydrological balance. In the context of a cloud forest, two distinct forms of influx can be distinguished: vertical precipitation, commonly known as ”conventional rainfall”, and horizontal precipitation, which encompasses the capture of cloud water by the canopy and is commonly referred to as ”fog interception”. The next two paragraphs delve into the specifics of these precipitation types and their contributions to the hydrological balance within cloud forests.

Vertical precipitation

Vertical precipitation occurs when ascending air undergoes cooling and condensation processes, leading to the formation of clouds. Eventually, the clouds form precipitation in different forms like rain, snow, hail, etc. In the case of cloud forests, the most common type of vertical precipitation is rain. A more elaborate explanation behind vertical precipitation can be summarised as follows:

1. Moisture-laden air approaches elevated terrain such as a mountain.
2. As the air rises over the mountain, its temperature decreases due to the decrease in atmospheric pressure with the altitude.
3. The cooling of the air prompts the condensation of water vapour, leading to the formation of clouds.
4. As the air continues to ascend, the water droplets in the clouds may combine and grow eventually becoming heavy enough to fall down as vertical precipitation [36].

Horizontal precipitation

Horizontal precipitation, phenomena such as dew, fog, and mist, is water vapour that is carried horizontally over the earth’s near-surface. In specific ecological environments, like cloud forests, this atmospheric water vapour can be carried at a higher altitude and thus over extended distances by prevailing winds [57]. When the wind carries this water vapour over a long distance and blows through the cloud forest, small droplets can be intercepted by surfaces, such as trees and plants, thereby providing a water source for the vegetation. It is noteworthy that horizontal precipitation typically contributes a relatively small proportion to the overall water influx within a hydrological balance. Nonetheless, cloud forests form an exception, where this particular type of precipitation assumes a substantial role in the overall water balance [79].

2.3.3. Interception Storage

Interception refers to the process of interrupting the flow of water within the sequence of events that transport it to streams. This interruption can occur through the presence of vegetation cover or by collecting water in depressions like puddles, as well as in topographical features such as rills and furrows [20]. The present vegetation intercepts precipitation and stores it on leaves, branches, mosses and other surfaces before it reaches the forest floor or evaporates. Cloud forests, which are characterised by persistent fog and high levels of precipitation, are particularly important sites for interception research. There are different types of interception that occur. The most important are canopy interception, stemflow, forest floor interception on leaves and moss interception [16]. An overview of the cloud water interception is visualised in Figure 2.1.

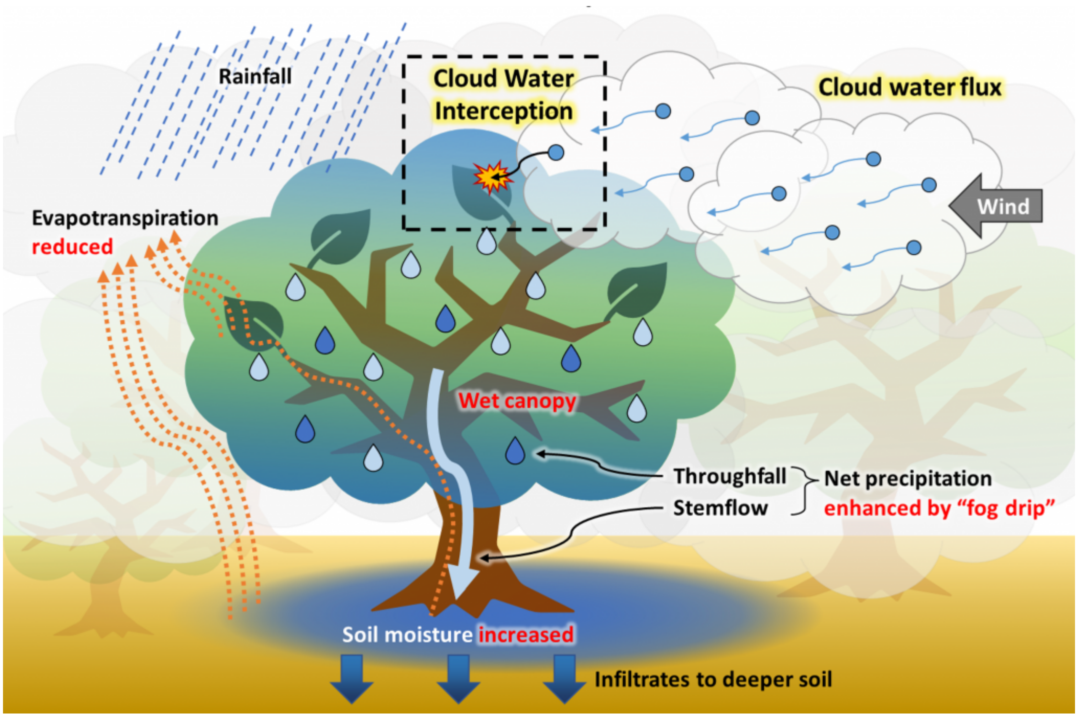


Figure 2.1: Overview of the enhanced processes occurring in cloud forests as a result of their characteristics [38].

Canopy storage capacity refers to the amount of water that can be stored temporarily on the leaves, branches, and stems of vegetation. A seminal investigation into the hydrological attributes of epiphyte masses within the TMCFs of Colombia conducted in 1990 unveiled the remarkable water-intercepting capabilities of non-vascular epiphytes [95]. These epiphytes effectively capture substantial amounts of rainfall, with a slow release through drainage and evaporation processes. In addition to non-vascular epiphytes, which serve as the primary storage component in this research, the overall canopy storage encompasses various other elements, namely vascular epiphytes, bromeliads, deceased organic material and tree foliage [35].

2.3.4. Canopy Outflux

The outflux of the canopy in the hydrological balance of the canopy is the sum of all the water that leaves the canopy, including the throughfall, stemflow and evaporation. The outflux of the canopy is typically expressed in millimetres, such as per hour, per day or per year. It is an important component of the hydrological balance of the canopy because it determines how much water ends up in the surface flow, subsurface flow and groundwater flow [15].

Throughfall

Throughfall, as defined in the literature, represents the precipitation that either passes directly through the canopy or is first caught by above-ground vegetative surfaces and then drips or splashes down the canopy [60]. This component significantly contributes to the canopy's hydrological balance, typically comprising approximately 50 to 80% of the total precipitation input [61]. In the case of cloud forests, research by L.A. Bruijnzeel in Guatemala suggests throughfall can account for as much as 80% of the total precipitation [10]. Notably, rain forests can experience even higher throughfall proportions, reaching up to 83 $\pm$ 8.8% in specific regions like Western Amazonia [25]. The magnitude of throughfall is subject to various factors including forest type, vegetation density, climatic conditions, seasonal variations and the overall precipitation volume [60].

Stemflow

Stemflow is a hydrological phenomenon wherein water flows down the trunk or stem of a tree, eventually reaching the ground. This process occurs when precipitation is intercepted by various parts of the tree, including its bark, branches and leaves, and subsequently flows downward along the tree's bark [5]. While stemflow typically constitutes a smaller fraction of the total precipitation compared to throughfall, it can still be a significant contribution to surface and groundwater dynamics. In the context of cloud forests, stemflow typically contributes 5 to 15% of the total precipitation. However, it varies depending on a number of factors, such as the type, density and size of the vegetation, the seasonal variations and the amount of precipitation. For example, in areas with densely vegetated forests, stemflow tends to be more substantial due to the increased surface area available which allows the precipitation to flow down, even though throughfall may be comparatively reduced. Additionally, a forest in a humid climate will have more stemflow than a dry climate because the humid climate promotes the growth of dense vegetation [10].

Evaporation

In the context of the hydrological cycle, evaporation is the process by which liquid water is converted into water vapour over a given area and subsequently enters the atmosphere. This process is driven by the radiant energy of the sun, which is the magnitude of solar radiation. As the water heats up, its molecules begin to move more quickly and gain more energy. Consequently, when these molecules have enough energy, they break free from the surface water and escape into the atmosphere [15]. The rate of evaporation depends on a number of factors, such as solar radiation, wind speed, humidity and surface area. This also includes transpiration, a process in which plants absorb liquid water from the soil and emit water vapour into the atmosphere through their leaves [91]. In Chapter 3, the influencing factors and the methodologies for the quantification of evaporation will be discussed in more detail.

2.4. Introduction to Hydrological Models

In this section, an introduction to hydrological models is given. The aim of a hydrological model is to simulate the hydrological cycle using a simplification of the real-world system. These simplifications and simulations of the hydrological cycle can be performed in different ways, resulting in different types of models. In this Section, two of such models will be explained. In section 3.5, the model developed for the catchment will be further elaborated on.

2.4.1. HBV Model

A Hydrologiska Byrans Vattenavdelning (HBV) model is a conceptual rainfall-runoff model, which is very common in the research of hydrology [4]. It is designed to simulate physical properties, aspects and relationships. Rainfall-runoff models are used to estimate runoff as a function of various parameters that describe catchment characteristics [23]. It does this by taking into account different hydrological processes, such as precipitation, snowmelt (not applicable to our research), infiltration, evapotranspiration, and runoff.

The best model is one that uses the fewest number of parameters, is as simple as possible and produces results that are very similar to reality. More parameters lead to either a larger simulation quantity and/or issues of equifinality. If the system is too large and/or there is too much variability in the system, lumped models fail to resolve the difference [44]. To give an example, a lumped HBV model may prove inadequate in capturing different forms of canopy cover and flux distribution within a partially cloud forest-covered catchment. To address this, one potential solution is the usage of a semi-distributed model, like the FLEX-Topo model.

2.4.2. FLEX-Topo Model

The FLEX-Topo model, a semi-distributed model, uses the same principles as the HBV model, but it is altered so that the landscape is classified based on topography. Topography is closely related to soil, climate and land cover. As a result, it may reflect the dominant hydrological processes in a catchment. FLEX-Topo uses elevation data indirectly, through Height Above Nearest Drainage (HAND) and slope. The landscape classes within the model include low drainage areas (low HAND and slope), hillslopes (high HAND and steep slope), and plateaus (high HAND and gentle slope). These landscape classes show slight variations in hydrological processes and contain different parameter sets in the classes [33]. The choice of the FLEX-Topo model for this project is grounded in its topographic emphasis, which is relevant in cloud forests. The classification of the model can also be altered such that it is a combination of landscape-based as well as topographically-based. This will be done in the project by inclusion of the leaf area index. The advantage of this approach is that it retains maximum simplicity, reducing computational cost, while still taking into account observable landscape characteristics [87].

2.4.3. Notes on Modelling

The primary challenge in hydrological modelling is to express the response of a catchment in terms of its state variables and characteristics [29]. Normally, a warm-up period is used to establish appropriate initial states for better calibration. However, due to limited measurement data in this project, the warm-up period cannot be applied. Also, because of the short historical data available, validation of the hydrological model is not feasible. The lack of validation makes overfitting a potential concern.

2.5. Introduction to the Key Stakeholders of CCFC

CCFC prioritises multi-level relationships, spanning from collaborations with local communities to national and departmental governmental bodies. These stakeholders are essential for achieving CCFC's mission and goals [18]. This section will provide an overview of the key stakeholders and existing policies relevant to CCFC's conservation efforts and mission. This overview is intended to define the landscape of stakeholders within which CCFC is conducting their work, explaining their responsibilities and relationships to CCFC.

2.5.1. Governmental Institutions

Governments are important stakeholders, as they create the legal and regulatory environment within Non Governmental Organisations (NGOs) function [59]. To expand this environment, NGOs have to present a clear plan of why they would like to and how this would benefit the values the government resembles. In this section, the relationship between NGOs and government is further explained.

National level

INAB

The Instituto Nacional de Bosques (INAB) is a government institution in Guatemala tasked with the management and preservation of forests and natural resources. INAB was established in 2001 under the Forest Law of Guatemala. Its mission is to regulate the sustainable use and conservation of forests and forest-related resources. INAB's objectives include the promotion of sustainable forest management, the protection of forest ecosystems, and the enhancement of social and economic benefits derived from forest resources. The institution is responsible for granting and regulating forest concessions, monitoring and enforcing forest laws and regulations and supporting forest-related research and development initiatives.

INAB has a regulatory oversight role, while CCFC works at the community level to engage local communities. INAB's regulations and permits affect CCFC in their reforestation and forest protection initiatives [45].

CONAP

Consejo Nacional de Areas Protegidas (CONAP) is a government institution in Guatemala responsible for the preservation and management of natural environments. CONAP is focused on environmental protection and biodiversity conservation. CONAP was established in 1990 under the General Law of the Environment and Natural Resources of Guatemala. Its primary mission is to safeguard the nation's protected areas, including national parks, wildlife reserves, and other ecologically sensitive regions. CONAP's main objectives encompass the protection, conservation, and sustainable management of Guatemala's natural heritage. This includes preserving biodiversity, promoting ecological research, and fostering environmental education and awareness. The institution has designated and manages a network of protected areas that cover approximately 30% of Guatemala's territory. Furthermore, CONAP has been actively engaged in reforestation initiatives, ecological monitoring, and wildlife preservation programs [19].

CONAP registers conservation zones and establishes regulations to protect those areas. CCFC's conservation zones need to be registered by CONAP and they need to comply with the regulations while conducting their conservation activities. Conducting research in natural settings requires approval from CONAP.

Forest incentive programs
Forest incentive programs are aimed at encouraging the maintenance of existing forests and the expansion of tree cover. There are two forest incentive programs active: the Smallholder Forestry Incentives Program (PINPEP, 2010-present) and the Program to Promote the Establishment, Recovery, Restoration, Management, Production and Protection of Forests (ProBosque, 2017-present). Both are managed by INAB, in collaboration with CONAP.

- *PINPEP*
  This stands for Forest Incentives Program Law for Owners of Small Areas of Land with a Forest or Agricultural-Forest Vocation. The program gives out incentives to plant trees or to manage natural forests. The program is special for small land owners of forestry or agroforestry land. The objectives of the PINPEP program are the active participation of small landowners in the benefits of economic incentives in forestry matters. It promotes the improvement of the standard of living of smaller and local communities. The program wants to contribute to socio-environmental and territorial management for mitigation and adaptation to the effects of variability and climate change, strengthening the resilience of forest ecosystems to support national efforts in food security, civil protection, water resources management, comprehensive rural development and reduction of risks to natural disasters. The goal is particularly to reach small landowners and therefore to reach local communities, including participation of the poorer people [45].

- *ProBosque*
  This is another forest policy instrument. It has a twofold objective: promoting forest plantations and agroforestry systems. It supports the sustainable management of natural forests. It encourages forest conservation and restoration in upper catchments, mangrove forests, and riparian zones, offering financial incentives to land owners for activities such as tree planting, forest maintenance, and protection. The ProBosque program is more focused on larger parcels of land [45].

Critique
According to research by the World Bank, the incentive programs receive multiple critiques regarding their efficiency and effectiveness.

- *Lack of efficiency*
  The efficiency of the program is low due to several institutional inefficiencies. The information and process management of INAB and CONAP are not automated and non-compatible with each other. Meaning that there is a weak exchange of interinstitutional information between INAB and CONAP. Also, monitoring of the program is done through physical visits, meaning that 90 percent of the total time of the personnel of INAB is dedicated to that. Next to this the intuitional staff do not all have the expertise and capacity to provide quality services. All this leads to excessive progress time. The time to approve a request is: 131 days for PINPEP and 471 days for ProBosque. While in the regulations a processing time should not exceed 60 days [99].

- *Lack of effectiveness*
  Information regarding incentive distribution is lacking, particularly for the PINPEP program, which is intended to benefit the poorer segments of society. Both incentive programs aim to combat deforestation, a problem strongly associated with poverty. Consequently, these programs should primarily target poorer communities. Although indigenous people are a major part of this category, they experience difficulties with accessing these programs. Firstly, there is limited awareness of

the existence of these initiatives due to ineffective outreach efforts. Also, language barriers and illiteracy are not taken into account during those campaigns and in preparing the necessary incentive paperwork. Secondly, the associated costs for submitting an incentive request are prohibitive, stemming from the need to travel to INAB offices and the preparation of a forest management plan [99].

Provincial level (Department of Alta Verapaz)

Ministry of Education (MINEDUC)

The Ministry of Education (MINEDUC) in Guatemala formulates and administers educational policies, ensuring the quality and accessibility of both public and private education in compliance with the law. Its primary objective is to transform the educational system with inclusivity and socio-cultural relevance, aiming to enhance students' capabilities in the learning process [64]. Responsibilities are given to departmental offices. Their responsibilities are promoting, coordinating and supporting educational programs that operate in their jurisdiction; seeking the expansion of educational coverage in their jurisdiction as well as improving the quality of the education. They have the responsibility to develop and implement educational initiatives tailored to the specific needs of the local community, including the execution and coordination of curriculum adaptation, development, and assessment in alignment with current national educational policies while considering local characteristics and requirements [63].

CCFC was able to collaborate with the Departmental Office of Alta Verapaz to successfully integrate environmental education into the educational curriculum of the region. CCFC assumed the responsibility of designing and implementing environmental education initiatives within the educational programs of Alta Verapaz.

2.5.2. Local Governance

In Guatemala, villages are situated within the administrative jurisdiction of municipalities. However, many governance responsibilities are delegated to village-level councils and committees. These village governance structures typically include a council referred to as Consejo Comunitario de Desarrollo (COCODE). Additionally, there are several committees, each assigned specific areas of focus such as Education, Health, Access, and Water. However, their practical responsibilities typically do not encompass concerns related to maintaining water quality or ensuring water availability [70]. COCODEs representing villages located around the Cahabón River have mentioned their concerns about water security among the local population. They have attributed water stress to factors like meteorological drought, deforestation, and population growth as was mentioned in the report of Cloud Chasers 1 [1].

CCFC maintains strong relationships with various village councils and committees in the villages where they operate. This collaboration is crucial because these local councils and committees hold significant responsibilities in the various areas where CCFC seeks to drive positive changes; like education, health and water security [18].

Community level

The remote villages surrounding the cloud forests are the centre of CCFC's efforts to combat poverty and protect the cloud forest ecosystems. The local population is predominantly Q'eqchi' Maya, and their worldview is deeply rooted in Maya traditions. CCFC's initiatives are designed to align with this worldview, fostering an understanding of the environment within the cultural context. Their community-based approach thrives on fostering ties within these communities and stands as the most viable strategy, given the social realities, geography, and their profound impact on the cloud forests. From the beginning, CCFC has developed relationships with families in these villages, particularly with young women and local schools [18].

2.6. Stakeholder Management Principles and Possible Interventions

There are numerous individuals and communities that rely and depend on the services of the cloud forests in the Mestelá River catchment. Simultaneously, various stakeholders play a significant role in shaping and influencing the cloud forest ecosystem through their actions. Conservation efforts of cloud forests in the department Alta Verapaz encompass a wide variety of challenges, involving multiple stakeholders with diverse and different interests.

2.6.1. Stakeholder Management

As described by Jonson and Scholes stakeholders are: "Those individuals or groups who depend on the organisation to fulfil their own goals and on whom, in turn, the organisation depends" [49].

In literature and practice, it is known that the management of these stakeholders is a crucial aspect. Stakeholder management involves identifying relevant stakeholders and analysing their concerns, interests and expectations [7]. Efficient stakeholder management guarantees that stakeholders' concerns and interests are taken into account in the development of solutions or initiatives. This ensures the alignment between the goals and initiatives of an organisation with the concerns and interests of its stakeholders. This approach creates support from the stakeholders for the organisational goals [85].

Stakeholder engagement is central to effective stakeholder management. Effective stakeholder management helps to develop and implement strategies to engage with stakeholders. Therefore stakeholder management involves the organisation, monitoring, and improvement of relationships with the involved stakeholders. This helps to maintain and build strong relationships. Making it possible to coordinate the various interactions [48, 30].

Next to that, problem-solving capabilities can be improved by effective stakeholder management and actively engaging stakeholders. Effective stakeholder engagement provides organisations with access to diverse perspectives, expertise, and knowledge. Engaging diverse stakeholders can bring new perspectives and ideas to the table, fostering innovation and creativity. Actively engaging stakeholders and involving them in the development of solutions allows for a comprehensive assessment of options and considers the implications of their actions on the various stakeholders [88].

Effective stakeholder management also contributes to better compliance with relevant laws, regulations, and policies. It involves a deep understanding of which policies are in place and the stakeholders with whom collaboration is essential. This strategic engagement enables organisations not only to remain compliant but also to leverage these laws and policies to their advantage [13].

Another benefit of effective stakeholder management is that it fosters open communication and relationship building. Transparent communication with stakeholders builds trust and encourages collaboration. When executed effectively, stakeholder management helps develop and sustain good relations with stakeholders. Stakeholder management can enhance an organisation's reputation by demonstrating a commitment to stakeholder concerns, ethical practices, and social responsibility. Organisations that actively engage with stakeholders tend to enjoy better relationships which can lead to increased stakeholder support, increasing possibilities for collaboration, and a positive reputation. A positive reputation also attracts support, partnerships, funding and can increase their influence [30, 31, 17].

Stakeholder management must be contextualised for CCFC, considering the unique challenges and opportunities faced in their socio-ecological initiatives.

2.6.2. Multi-Stakeholder and Multi-Issue Environment

The stakeholder landscape within which CCFC operates is quite complex and diverse, involving numerous stakeholders. This landscape can be seen as a multi-stakeholder system. A multi-stakeholder system can be described as the presence of multiple stakeholders who pursue divergent or partially overlapping issues or objectives, through which they depend on each other [69].

A multi-stakeholder system represents an interdependent system of a diverse range of stakeholders who are connected through relationships and interactions with each other within a specific context, in the context of CCFC this is the cloud forest ecosystem and the related catchment. Ecosystems are complex and subject to a large amount of internal and external relationships [66]. Stakeholders are not a homogeneous group but come from diverse backgrounds and levels of authority [12]. These stakeholders shape and influence the experience of other stakeholders doing it intentionally or unintentionally [96]. Within such multi-stakeholder systems, stakeholders depend on each other's resources, expertise, or support to achieve their common goals or to address complex challenges [51, 21].

The interconnections within this system also extend to the issues and challenges these stakeholders are experiencing. These stakeholders may have diverse concerns, varying objectives, and different levels of interest in the interrelated issues, reflecting their unique challenges and strategies [12]. Because of this interdependence between the issues means they cannot always be addressed in isolation, as they influence one another. When considering this diversity of interests and issues, it's essential to consider the potential conflicts that may emerge among these interests and issues [46, 21]. Managing this system of stakeholders, each with their interconnected issues requires a deep understanding of the relationships between the various stakeholders and how their interests align or diverge. This understanding guides the process of engaging, disengaging, or collaborating with stakeholders to effectively achieve goals.

Distinguishing between internal and external stakeholders, it's important to note that while formal agreements within an organisation are typically governed by legal documents like contracts and laws (pertaining to internal stakeholders), the interactions and relationships among stakeholders in this multi-stakeholder system often lack such formal structures (external stakeholders) [65]. In the multi-stakeholder system, where formal agreements are often absent, it's important to recognise that no single actor holds the authority to impose solutions independently. The relationships with external stakeholders rely heavily on collaboration, negotiation, and the exchange of information [26]. Furthermore, it's crucial to understand that the multi-issue environment extends beyond the control of any single actor. The complexity and interconnected nature of the challenges at hand make it impossible for a single actor to fully manage or govern the situation or issues at hand, all have partial responsibility to act [12]. Instead, it necessitates the collective efforts of multiple stakeholders to address the diverse range of issues and interests present in this complex system [24].

Bryson underscores that stakeholders play a pivotal role in shaping an organisation's strategy and the achievement of its goals [12]. As described above and recognised by Bryson many stakeholders possess resources, expertise, or support that an organisation may require to implement its strategies effectively. For example, they may provide funding, knowledge, or advocacy. Organisations that acknowledge and engage with stakeholders in a meaningful way are better positioned to develop strategies that align with diverse interests and values while also achieving their goals effectively. Ignoring or mismanaging stakeholders can lead to challenges and hinder an organisation's success. Therefore, having a deep understanding of the complex multi-stakeholder system is valuable for understanding, engaging, and collaborating with this multifaceted network of individuals and groups [12].

Stakeholder management becomes even more important in these interconnected multi-issue and multi-stakeholder environments [12]. These systems are characterised by their complexity and the need to manage and navigate the interactions and relationships among these diverse stakeholders. Effectively managing these interactions is essential for achieving successful outcomes in such complex systems. Engaging multiple stakeholders ensures diverse perspectives, unique insights, experience and expertise are brought to the table, improving the likelihood of finding effective solutions [66].

As mentioned in **??** **...REFerence** the landscape within which CCFC operates is complex and diverse, involving numerous stakeholders and issues. If CCFC wants to achieve its goals, it needs the cooperation of a whole range of stakeholders, not only governmental authorities on the national and local level but also on the community level [26]. Successful stakeholder management helps in reaching more effectively and efficiently their goals.

2.6.3. Interventions

Interventions are dynamic tools that can help to bridge the gap between research findings and practical actions. They can take various forms and may have different goals to achieve. They play a pivotal role in addressing complex issues and achieving positive outcomes [50].

Interventions serve as a means to convey critical messages, raise awareness, and engage stakeholders in a meaningful way. The primary role of interventions is to share knowledge and understanding about the issues at hand with the involved stakeholders, generate interest and capture attention from stakeholders or drive behavioural change, by influencing stakeholders' practices and behaviours. The nature of interventions can vary [92]. As mentioned in 2.1.2 CCFC has two pillars, environmental and social. Therefore in this literature review, we will look at social and environmental interventions.

Environmental interventions

Environmental and Conservation Interventions are strategies and actions aimed at preserving and protecting the natural environment. These interventions are essential for addressing environmental challenges. They can be carried out by governments, NGOs, or even individuals. Such interventions encompass diverse strategies and actions. These interventions can be categorised into three key groups: command-and-control/disincentives (e.g., protected areas), incentives (e.g., Payment for Ecosystem Services), and enabling measures (e.g., capacity-building) [73]. Effective environmental and conservation interventions have key features that include sustainable land and resource management, biodiversity conservation, habitat restoration and community engagement [98]. Community engagement is less of a direct intervention, but successful environmental and conservation interventions often involve local communities and other stakeholders. This engagement fosters support, knowledge sharing and a growing shared responsibility for the environment [37].

Social interventions

In the domain of community and social interventions, actions are designed to address a wide array of societal issues. These interventions target specific communities or groups, recognising their unique needs and circumstances. They serve as essential tools for addressing complex social issues and driving positive change at the community level. These interventions typically focus on improving the well-being, relationships, and overall quality of life. They are often implemented by government agencies, nonprofit organisations, or community leaders to promote positive social change and address issues such as poverty, education, healthcare, social justice, and more. Social interventions often seek to create sustainable, long-term change within the community by building local capacity, fostering collaboration, and empowering individuals and groups to continue and expand the impact of the intervention. They often involve the active participation and engagement of community members or stakeholders in the planning, decision-making, and implementation processes. This participatory approach aims to ensure that interventions are relevant and effective. Key characteristics of community and social interventions include local focus, participation, social impact, a holistic approach, long-term sustainability, and empowerment of individuals and groups [56, 72, 73, 67].

Interventions used by CCFC will involve a holistic approach, recognising the interconnections of environmental challenges and social challenges.

The choice between a ”bottom-up” or ”top-down” approach for interventions depends on the specific context and objectives of the intervention. Table 2.1 gives an overview of the advantages.

In practice, many interventions may combine elements of both approaches. This involves for example using top-down guidance and resources to support and facilitate bottom-up participation. The choice of the approach should be based on the specific objectives, context, and stakeholders involved in the intervention. It’s important to consider which approach best aligns with the desired outcomes and the capacity of stakeholders to participate effectively [62, 34, 80].

While interventions offer promising pathways for change, they come with their challenges. Their effective implementation requires planning, stakeholder engagement, and ongoing evaluation. To ensure that interventions are effective, it’s essential to measure their impact through for example pre- and post-intervention assessments or monitoring indicators. Monitoring is vital for ensuring the intervention’s effectiveness and efficiency. It enables the assessment of whether the initiative is meeting its intended goals and objectives and aids in determining if desired outcomes are being achieved. Furthermore, monitoring is essential for continuous learning and adaptation. By collecting data on what works and what doesn’t, such as its resonance with the children, provides valuable insights that can lead to ongoing improvements and the refinement of our approach over time [73].

Table 2.1: Overview advantages top-down and bottom-up interventions.

Advantages top-down	**Advantages bottom-up**
Centralised Control: decision-making and control are typically centralised at higher levels of authority [80, 34, 42]	*Local Empowerment*: decision-making and control are decentralised, involving local communities, grassroots organisations, or individual stakeholders [80, 34, 42]
Efficiency: making it possible to implement policies and initiatives on a large scale, allowing for uniform implementation across a wide area [80, 34]	*Community Engagement*: active involvement and engagement of local communities or stakeholders, which can lead to solutions that are more contextually relevant [80, 34]
Clear Accountability: Accountability is clear, responsibility for the implementation and action lies with higher-level authorities. [34]	*Tailored Solutions*: Bottom-up approaches allow for the development of tailored solutions that address specific local needs and concerns [80]
Resources: Top-down approaches may benefit from the resources available at the centralised level [34]	*Ownership*: Stakeholders have a sense of ownership and are more likely to be committed to the success of the intervention because they have been actively involved in its design and implementation [80, 34]
	Inclusivity: This approach promotes inclusivity and may lead to more equitable outcomes, as it takes into account diverse perspectives and local knowledge [80, 34, 42]

3

Methodology

In this chapter, the methodology of the project is described. The research is divided into three stages so that the research question can be answered. In the first stage, the different parameters of the cloud forest canopy are quantitatively determined and analysed. For the second stage, the Mestelá River catchment is analysed and the total water discharge is determined. The results of these two stages are eventually combined to give a total overview of the correlation between the cloud forest canopy and the Mestelá River water discharge. With this information, stakeholder interviews are conducted.

3.1. Mestelá River Catchment Delineation

As shown in Figure 1.1, the Mestelá River is a tributary of the Cahabón watershed. The actual outflow boundary of the Mestelá River catchment is around the water extraction point, as seen in Figure 3.1. However, the boundary of the catchment area has been moved upstream such that the outflow is at the stilling well on the CCFC property, which will be further discussed in Section 3.5. This adjustment was made to align the outflow, measured at the stilling well, with the fluxes entering the model. The remainder of the project refers to the Mestelá River catchment as the attributing area upstream of the stilling well.

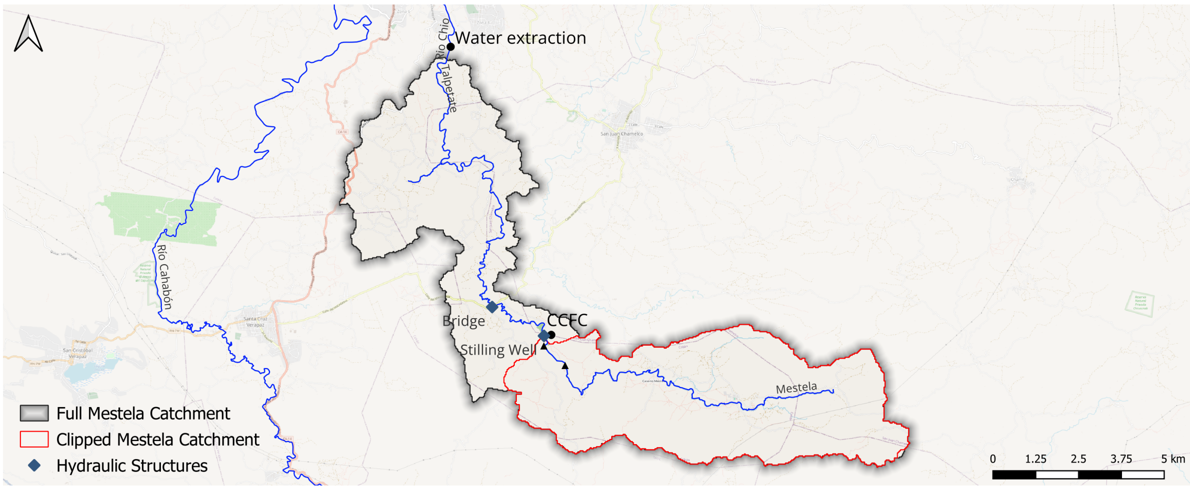


Figure 3.1: Mestelá River catchment indicated in black. The clipped catchment of the Mestelá River is shown in red. The clipped area is the contributing area of the Mestelá catchment upstream from the stilling well.

The catchment delineation was conducted in QGIS using the PCRaster plugin developed by Hans van der Kwast. The PCRaster plugin is especially useful and well-functioning in hydrological modelling and analysis [54]. The delineation of the catchment takes as only input the Digital Elevation Model (DEM), which was converted into a compatible PCRaster format. From there, the Local Drain Direction (LDD) was derived, providing a general indication of water flow directions, such as north, northeast, east, and so on.

With the LDD, the stream order (also known as Strahler order) was created, resulting in a raster classification ranging from 0 to 12. To define the catchment streams, a threshold value of 5 was chosen, so that order of 6 and higher will be exported as the streams in the catchment. This threshold was visually validated through comparison with the OpenStreetMap. It's important to note that due to the 30x30-meter raster grid and human activity affecting river flow, the resulting stream flow raster is only an estimation of actual river flow based on elevation, as depicted in Figure A.1 in Annex A. We chose not to burn[1] the actual river flow from the OpenStreetMap into the DEM, since this will also alter the results of further analysis. After selecting an outflow cell nearest to the stilling well, the catchment boundaries were derived with the LDD raster. The total area of the Mestelá catchment upstream from the stilling well is 34.1 km^2, or 3410 hectares.

3.2. Measurement Site for Canopy Monitoring

One of the project's objectives was to establish a long-term measurement site to collect data related to the hydrological cycle of the Mestelá River catchment. In this chapter, the location of the measurement site is elaborated on. Next, a reconnaissance of the measurement site is performed and a summary of all equipment is given.

3.2.1. Decision Location Measurement Site

The location of the measurement site was based on the following considerations: security, proximity, accessibility, internet connection, cloud cover presence and height within the catchment. The previous group recommended installing the measurement site in the reserve of Ranchitos del Quetzal or on the private grounds of CCFC. However, Ranchitos del Quetzal is not inside the boundaries of the Cahabón watershed, making it irrelevant to the scope of this research. After conducting several field trips, the following three potential sites were selected:

1. Brecha: This site is situated at 1792 meters above sea level and is located just outside of the border of CCFC.
2. Hillside CCFC: This option is at an elevation of 1655 meters, is located on the property of CCFC but is also the lowest of the three options (referred to as 'site' in Figure 3.2).
3. Xucaneb: This site is located on the southern borders of the catchment and is the highest point at 2628 m. This site features a radio tower atop the mountain and is continuously guarded.

In Figure 3.2, the location of the three sites is presented. In coordination with the directors of CCFC, it was concluded that Hillside CCFC is the best location for the long-term setup. This conclusion is based on multiple pros and cons that are explained in Table 3.1.

[1]To burn river flow through QGIS analysis is to alter the raster DEM values so that the Strahler results better follow the actual river location.

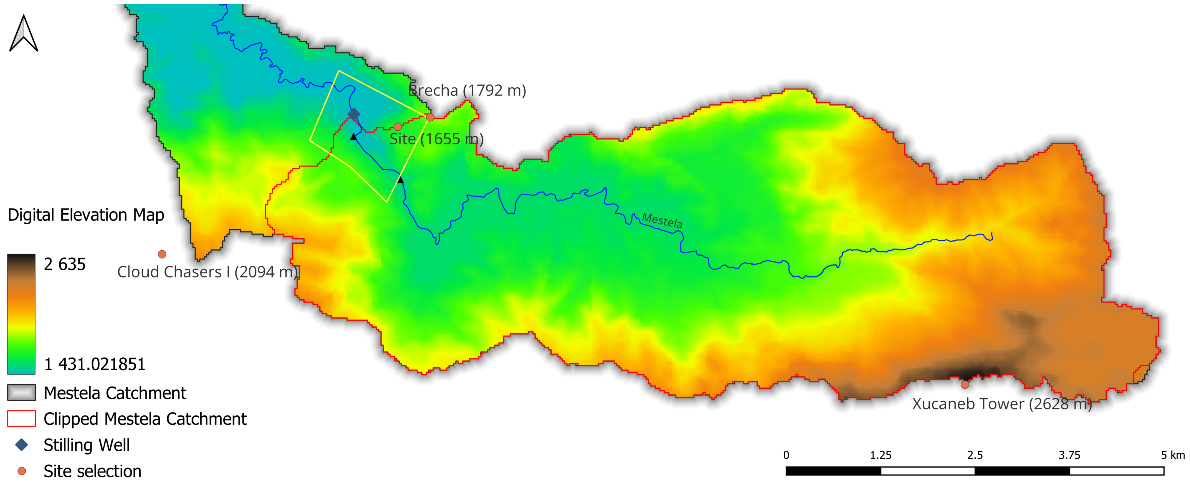


Figure 3.2: Locations of the different site options shown in orange. The decided location of the measurement site is called "site" in the figure. The property of CCFC is indicated in yellow.

Initially, the site Xucaneb seemed like the preferred location due to its security against potential theft and the frequent presence of clouds. However, one major drawback of Mount Xucaneb was its lack of internet connectivity, which was a crucial requirement for our project. Within the proximity of Brecha, some well-travelled trails existed, as well as some logging activity to the east. These logging activities resulted in the rejection of the Brecha site by the directors of CCFC. As a result, the Hillside CCFC was selected as the site for the long-term setup.

Table 3.1: Table of the pros and cons of the different sites, which was used to decide the location. The decided location for this project is "Hillside CCFC", indicated in green.

Location	Hillside CCFC (++)	Mount Xucaneb (--)	Brecha (-)
Pros	+ Close by, simplifying maintenance + On the land of CCFC + Altitude is more typical for the area + Guaranteed internet connection	+ Cloudy area, resulting in more data on fog interception	+ Close by, simplifying maintenance + Altitude is more typical for the area
Cons	- Less significant cloud interception - Risk of damage or tree felling due to no surveillance	- Car needed for transportation - Extra people needed to help carrying the equipment - Altitude is not typical for the area - Little to no internet connection HOBOLink	- Not cloudy and humid enough - Not guarded or on the land of CCFC - No trail available, leads to safety risks and logistical challenges

3.2.2. Introduction to Measurement Site

This section is meant to give a brief introduction and reconnaissance of the measurement site. The following points characterise the measurement site:

- Elevation: 1655 m, which is relatively low for the catchment.
- Slope Orientation: South-oriented, with the prevailing wind direction being southeast. This orientation facilitates fog interception as clouds pass through the trees.
- Experimental Area: The dimensions of the site are 10 m by 15 m.
- Measurements: At the site, the following measurements are performed; horizontal precipitation, throughfall, soil moisture content and stemflow.
- Tree selection: Within the experimental area, one large oak tree was found with a circumference of 3.7 meters. This tree was used to install the canopy measuring devices.

In Table 3.2, an overview is given of the different types of equipment that were used at the measurement site. Furthermore, improvements have been made to extend the product lifetime of the measurement site. Because the goal is that the measurements continue after the project's completion. These enhancements include protecting cables from insects and vandalism with plastic pipe covers, adding filters to gutters and fog traps to prevent tipping bucket clogs, and installing the HOBO station at a minimum height of 2 meters to discourage vandalism. In Figure 3.3, an overview of the site is given, showing the location of the throughfall gutters, the tipping bucket and the soil moisture sensor. In Appendix D, the specifications of the sensors and the station are found.

Table 3.2: An overview of the equipment used at the measurement site, including the dimensions. Further details about the measurements can be found in Section 3.3.

Measurement type	Equipment	Dimensions
Horizontal precipitation	3 Fog traps 1 Tipping bucket 3 Funnels 3 Connection tubes (garden hoses)	Installation height: 14 m Diameter fog trap: 0.20 m Height fog trap: 0.46 m
Throughfall	4 Gutters 1 Tipping bucket 4 Funnels 4 Connection tubes (PVC-pipes)	Diameter gutter: 0.1 m Length gutter: 2.5 m Total collection area: 1 m^2
Soil moisture content	1 Soil moisture sensor	Installation depth: 0.4 m
Stem flow	1 Cut-open tube 1 Diver 1 Collection bottle	Circumference stem: 3.7 m Diameter tube: 0.03 m Length tube: 7.4 m Volume bottle: 14 L
Data collection	1 HOBO station 1 Solar panel	

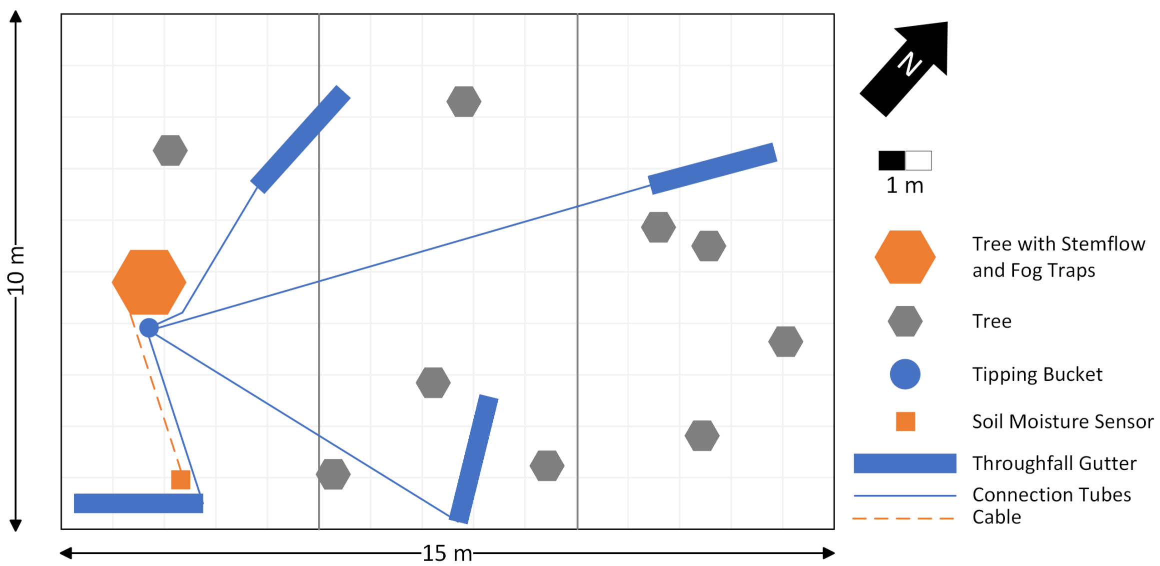


Figure 3.3: Top view of the site (10 by 15 meters). The tree which was used for measuring the stem flow and the installation of the fog traps is indicated as an orange hexagon. The soil moisture sensor and the tipping bucket are also located close to this large tree because the HOBO station was located there as well. The other trees, with a diameter larger than 0.3 m, are indicated as a grey hexagon. The throughfall gutters are indicated as blue bars.

3.3. Canopy Monitoring

This paragraph describes the different measurements done at the site, as well as the data collection devices, data conversions and calculations.

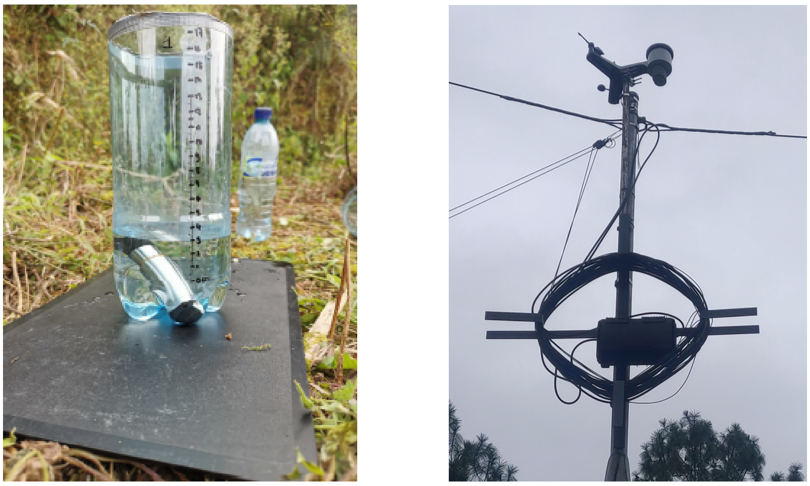
3.3.1. Canopy Influx

As mentioned in Section 2.3, the influx of the canopy in cloud forests can be divided into two parts: vertical precipitation and horizontal precipitation. Both of these forms of precipitation are crucial for understanding the hydrological balance of the canopy.

Vertical precipitation

To assess vertical precipitation, various methods can be employed. One such approach, utilised by Cloud Chasers I [1], involves the development of homemade rain gauges created from 3L water bottles. Figure 3.4a shows an example of a homemade rain gauge made by Cloud Chasers I. These homemade instruments offer a straightforward way of collecting vertical precipitation and are accessible for the local communities to use. The water collected in these bottles is measured using a pressure sensor known as a ”diver”. However, for this research, which aims for a long-term setup, homemade rain gauges would not serve the needs, as the diver has to be replaced after a while to collect the data.

Consequently, a weather station (ICOBN4, Figure 3.4b) located in the surrounding of the experimental area is used for this research, which is still situated on the grounds of CCFC. This specific station is an Alecto WS-5500 weather station connected to the online platform Weather Underground. The weather station provides plenty of information, including temperature, dew point, humidity, wind speed and gusts, air pressure, precipitation and incoming solar radiation. Data is provided with an interval of 5 minutes.



(a) Homemade rain gauge by Cloud Chasers I [1]

(b) Weather station ICOBN4

Figure 3.4: Various methods to measure vertical precipitation.

For the assessment of vertical precipitation, the data from the weather station is used as input data. Other measurements from the weather station are used to calculate different input parameters, which will be discussed later. It is important to note that this reliance is based on an assumption since the weather station is not located in the experimental area. Nevertheless, the measurements obtained are considerably more accurate than those from a homemade device. Furthermore, the weather station is still within the catchment and the distance between the weather station and the experimental area is only about 800 meters.

Horizontal precipitation

Measuring horizontal precipitation, or in other words, fog interception by the canopy, comes with challenges. The diverse amount of vegetation types, each with unique interception capabilities, makes it difficult to obtain a precise estimate of intercepted fog. To obtain insights into the temporal distribution and variation of potential fog deposition, homemade ”fog traps” are used. It is important to note that these fog traps provide an indication and do not fully reflect the characteristics of the vegetation to capture the fog.

Cloud Chasers I developed an initial prototype of the fog trap, a cylindrical wire harp fog trap inspired by previous studies [6, 32, 82]. They identified various factors influencing the fog trap’s efficiency. While the goal of the fog trap is capturing horizontal precipitation, there is a possibility of measuring vertical precipitation as well. Their prototype includes a roof shield intended to block a part of the vertical precipitation. However, due to the fog trap’s open structure and the angle of incoming vertical precipitation, it still affects the measurements. Moreover, efficiency is influenced by wind speed and drop size, which are accounted for in their design.

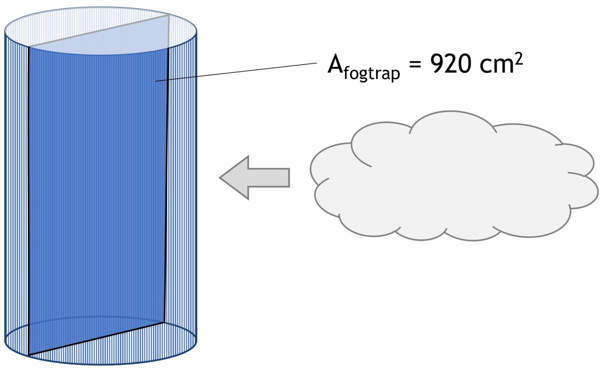


Figure 3.5: Cross-sectional area fog traps, which is used to calculate the correction factor.

The fog trap is constructed using a nylon fishing line and has dimensions of 46 cm in height, 20 cm in outer diameters and a cross-sectional area of 920 cm^2 for capturing fog. A visualisation of how the cross-sectional area is determined is visible in Figure 3.5. This collection surface comprised vertically arranged 0.5 mm nylon fishing lines spaced 2 mm apart. The nylon threads are wound around a saw blade with 2 mm spacing to ensure an even distribution. The plastic cover, originally with a diameter of 40 cm in length in the first prototype, was replaced with a plastic cover of 70 cm in diameter in this study to account for the measurement of vertical precipitation by Cloud Chasers I. Figure 3.6 provides a visual comparison between the initial prototype created by Cloud Chasers I and the fog trap developed for this research. Notably, the larger size of the plastic cover is clearly visible.

(a) Fog trap by Cloud Chasers I [1] **(b)** Improved fog trap by Cloud Chasers II **(c)** Improved fog trap by Cloud Chasers II

Figure 3.6: Comparison between fog traps of Cloud Chasers I & II

In total, three fog traps are utilised to measure horizontal precipitation, strategically positioned around the tree at approximately 14 meters in height. These fog traps are hung on big branches, with attachments to lower branches for stability, as visualised in Figures 3.6b and 3.6c. The water collected by the fog traps is channelled through hoses (Figure 3.7a) affixed to the fog traps and is eventually directed to a tipping bucket (Davis, S-RGF-M002), as shown in Figure 3.7b. This tipping bucket has a precision of 0.2 mm when it tips. To avoid dirt clogging in the tipping bucket, a filter is installed between the tipping bucket and the hoses, as can be seen in Figure 3.7c. The tipping bucket is connected to a data logger that transmits the data to an online server, facilitating data retrieval.

(a) Hoses channelling the water **(b)** Tipping bucket in the tree **(c)** Filter between tipping bucket and hoses

Figure 3.7: Overview of the tree including hoses, tipping bucket and filter

3.3.2. Interception and Storage of Non-Vascular Epiphytes

In this section, we focus on the interception and storage properties of epiphytic mosses. In this case, only non-vascular epiphytes are considered, as described in Section 2.3, as these organisms cover approximately 80-90% of branches and vegetation in our research area. The thickness of the mosses depends on branch thickness and inclination, as shown in previous research [95]. The moss thickness varies from 1-2 cm at the junction of primary branches with the trunk to 10-20 cm when positioned more than a meter from a primary branch. Secondary or tertiary branches typically exhibit minimal moss cover, generally less than 1-2 cm. Additionally, large “moss balls” exceeding 20 cm are observed, typically forming on primary branches.

Storage capacity of non-vascular epiphytes

To assess the storage capacity of non-vascular epiphytes, we drew inspiration from a study conducted by Veneklaas E. et al. [95] in the high TMCF regions of Colombia. This approach involved determining the interception capacity of mosses through a mass balance analysis, considering variations in moss weights across various moisture content conditions.

The moss samples can be assessed under three conditions: when fully saturated (W_{sat}), which means they are weighted initially when they are removed from the branches; after gentle wringing ($W_{squeezed}$); and after undergoing air drying throughout a dry spell (W_{dry}). The choice of air drying over oven drying, as practised by Veneklaas E. et al. [95], was made to replicate the authentic field conditions, particularly during wet periods following droughts.

From these measurements, three distinct portions of water can be delineated: total water retention (WR_{total}), externally held water ($WR_{external}$) and internally held water ($WR_{internal}$).

$$WR_{total} = \text{Saturated Weight} - \text{Dry Weight} = W_{sat} - W_{dry} \quad (3.1)$$
$$WR_{external} = \text{Saturated Weight} - \text{Squeezed Weight} = W_{sat} - W_{squeezed} \quad (3.2)$$
$$WR_{internal} = \text{Squeezed Weight} - \text{Dry Weight} = W_{squeezed} - W_{dry} \quad (3.3)$$

These portions of water can be expressed as percentages of dry weight.

$$WR_{total} = \frac{W_{sat} - W_{dry}}{W_{dry}} \tag{3.4}$$

$$WR_{external} = \frac{W_{sat} - W_{squeezed}}{W_{dry}} \tag{3.5}$$

$$WR_{internal} = \frac{W_{squeezed} - W_{dry}}{W_{dry}} \tag{3.6}$$

Evaporation of non-vascular epiphytes

We identified two distinct phases in the drying process of saturated mosses:

1. The drainage phase: during which water, seemingly exceeding the retention capacity, is rapidly lost primarily through dripping. The drainage phase was considered complete when the rate of dripping fell to less than one drop per minute.
2. The evaporation phase: where water loss occurs solely through evaporation. It's important to note that some evaporation also takes place during the drainage phase but at significantly lower rates compared to the drainage rates [95].

To estimate the evaporation occurring during the day, we calculated the weight loss over a period starting one hour after the conclusion of the drainage phase. The mosses were experimentally wetted. In Figure 3.8, the measurement setup of the experiment is shown. This is a typical epiphyte mass with some proportion of vascular and non-vascular plants.

Figure 3.8: The measurement setup related to the experiment of the evaporation of water in epiphytes.

3.3.3. Canopy Outflux

The outflux of the canopy consists of three parts: throughfall, stemflow and evaporation. These three parts are discussed in the following sections.

Throughfall

In order to quantify the throughfall within the study area, four gutters are constructed, each measuring 250 cm in length and 10 cm in width. These gutters collectively cover an area of 1.0 m^2 and are placed beneath the canopy to collect the throughfall. Figures 3.9 and 3.10 give an overview of the gutters in the study area to collect throughfall. Given the non-uniform nature of the tree canopy, with variations in spatial distribution, the gutters are randomly positioned under the canopy to provide a representative sampling of the average throughfall throughout the study area. These gutters are connected via PVC pipes to a single tipping bucket (Davis, S-RGF-M002), which is connected to a central data logger (HOBO, RX3000). This data logger transmits the data every 15 minutes.

Figure 3.9: Overview of the gutters collecting throughfall at the measurement site.

Figure 3.10: Details of the gutters.

To maintain the efficiency of the throughfall collection system, measures are taken to prevent debris from interfering with the process. Chicken wire is applied to the gutters to act as a barrier against falling debris and potential blockages. Furthermore, fine sieve filters were introduced within each gutter and the tipping bucket to prevent the accumulation of dirt.

The incorporation of a tipping bucket system reduced the need for frequent manual maintenance, as the data was transmitted through an online platform. However, routine visual inspections were conducted on a weekly basis to ensure the proper functioning of the system and to address any potential disturbances caused by new debris within the water collection system.

Stemflow

To quantify the stemflow from the tree, a PVC tube with a 3 cm width is wrapped around the trunk of the tree. This tube was carefully cut along its length to form a flexible gutter that could be adapted to the tree's irregular contour. To ensure a tight seal between the tube and the tree trunk, the tube made two complete loops around the trunk, effectively sealed with silicone sealant. Given that the tree had a diameter of 3.7 meters, the tube required a minimum length of 7.4 meters to complete two full loops, a requirement based on prior research by [16].

The stemflow was channelled into a large plastic container for precise measurement. Within this container, a diver (VanEssen, DI801) was placed to gauge the water pressure. Another diver was positioned externally to measure the atmospheric pressure, enabling compensation when determining the water pressure. These divers collected data at 15-minute intervals, and once a week, they were retrieved for data download. Using the recorded water pressure data and the container's surface area, we calculated the total stemflow volume accurately.

Figure 3.11: Overview of the tree collecting stemflow.

Potential evaporation

To calculate the potential evaporation, the Penman-Monteith formula (Equation 3.7) is used instead of the Penman formula. This choice arises from the fact that the Penman formula is suitable for estimating the potential evaporation of open water surfaces, while the Penman-Monteith formula is valid for vegetated surfaces [101]. As the soil and vegetation in the study area remained consistently wet, the actual evaporation within the cloud forest could be considered approximately equivalent to the potential evaporation. The measurement data from the weather station ICOBN4, which is close ($\pm$ 800 meters) to the study area), are used in the calculation of the potential evaporation. Table 3.3 summarises the parameters used in the Penman-Monteith equation.

$$E_p = \frac{\frac{s(R_N - G)}{\rho\lambda} + \frac{c_p \rho_a}{\rho\lambda}\frac{e_s - e_a}{r_a}}{s + \gamma\left(1 + \frac{r_c}{r_a}\right)} \tag{3.7}$$

In the next paragraphs, each parameter of the Penman-Monteith formula is discussed in a logical order, following the methods used in previous research [100].

The aerodynamic resistance r_a is determined based on the wind speed at 2 m elevation u_2 obtained from the weather station ICOBN4, using Equation 3.8.

Table 3.3: Parameters of the Penman-Monteith equation.

Symbol	Parameter	Unit
E_P	Potential evaporation	m/s
s	Slope of saturation vapour-pressure curve	kPa/K
R_N	Net radiation at the Earth's surface	J/(s m^2)
G	Ground heat flux	J/(s m^2)
ρ	Density of water (= 1000 kg/m^3)	kg/m^3
λ	Latent heat of vaporisation (= 2.45e6 J/kg) [100]	J/kg
c_p	Specific heat of air at constant pressure (= 1004 J/(kg K)) [100]	J/(kg K)
ρ_a	Density of air (= 1.2 kg/m^3)	kg/m^3
e_s	Saturation vapour pressure for temperature at 2 m elevation	kPa
e_a	Actual vapour pressure of air at 2 m elevation	kPa
r_a	Aerodynamic resistance	s/m
γ	Psychrometer constant (= 0.0669 kPa/°C) [74]	kPa/K
r_c	Canopy diffusion resistance (= 150 s/m) [100]	s/m

$$r_a = \frac{245}{0.54u_2 + 0.5} \tag{3.8}$$

Saturation vapour pressure for temperature at 2 m elevation e_s is calculated based on the temperature T in Kelvin, as can be seen in Equation 3.9. This formula is known as the Tetens Equation [90]. It is important to note that there is a clear difference in the formula for temperatures above and below 0°C. The formula used in this study is applicable for temperatures above 0°C, as it maintains a constant value above this threshold in this area.

$$e_s = 0.61078 \exp\left(\frac{17.27T}{T + 237.3}\right) \tag{3.9}$$

The actual vapour pressure of air at 2 m elevation can be calculated using Equation 3.10 and is derived from e_s and the relative humidity h [-].

$$e_a = e_s \cdot h \tag{3.10}$$

The slope of the saturation vapour-pressure curve s is calculated using e_s and the temperature T in Kelvin.

$$s = \frac{4098e_s}{(T + 237.3)^2} \tag{3.11}$$

Net radiation at the Earth's surface R_N is more complex to calculate and takes more intermediate steps. The net radiation is composed of two components: net short-wave R_{ns} and net long-wave R_{nl} radiation.

$$R_N = R_{ns} - R_{nl} \tag{3.12}$$

Equation 3.13 describes the net short-wave radiation, denoted as R_{ns}, and its unit of measurement is in $\left[\frac{J}{s\,m^2}\right]$. R_{ns} is dependent on a parameter known as the Albedo r specifically for cloud forests, with a value of 0.12 [-], as documented in [89]. The Albedo signifies the fraction of sunlight that is diffusely reflected by an object and it is quantified as a fraction between 0 and 1. In this scale, 0 corresponds to an object that absorbs all incoming light, while 1 signifies an object that reflects the entirety of incoming radiation. Furthermore, the net short-wave radiation is dependent on the incoming short-wave radiation on the Earth's surface R_{in}. This value can be extracted from the weather station ICOBN4 and is expressed in $\left[\frac{J}{s\,m^2}\right]$.

$$R_{ns} = (1 - r)\ R_{in} \tag{3.13}$$

The net long-wave radiation, referred to as R_{nl} and measured in $\left[\frac{J}{s\ m^2}\right]$, is the second component of R_N. Its calculation is detailed in Equation 3.14, according to [100]. This equation involves various factors. It relies on variables such as n and N, where n signifies the actual hours of sunshine recorded at the weather station ICOBN4, and N represents the mean daily duration of maximum possible sunshine hours. The value of N f0r each month can be extracted from Table 3.4 and varies for different months. The latitude of the experimental area is situated at 15°North, resulting in a value of 11.8 for N in the month of October. Additionally, R_{nl} depends on two other parameters: the actual vapour pressure of air at 2 m elevation e_a, which is computed in preceding sections, and the temperature T in Kelvin.

$$R_{nl} = \left(0.9\frac{n}{N} + 0.1\right)(0.34 - 0.139\sqrt{e_a})\,\sigma\,(T + 273)^4 \tag{3.14}$$

Table 3.4: The mean daily duration of maximum possible sunshine hours [77].

Northern Lats	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec
Southern Lats	July	Aug	Sept	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	June
50°	8.5	10.1	11.8	13.8	15.4	16.3	15.9	14.5	12.7	10.8	9.1	8.1
48	8.8	10.2	11.8	13.6	15.2	16.0	15.6	14.3	12.6	10.9	9.3	8.3
46	9.1	10.4	11.9	13.5	14.9	15.7	15.4	14.2	12.6	10.9	9.5	8.7
44	9.3	10.5	11.9	13.4	14.7	15.4	15.2	14.0	12.6	11.0	9.7	8.9
42	9.4	10.6	11.9	13.4	14.6	15.2	14.9	13.9	12.6	11.1	9.8	9.1
40	9.6	10.7	11.9	13.3	14.4	15.0	14.7	13.7	12.5	11.2	10.0	9.3
35	10.1	11.0	11.9	13.1	14.0	14.5	14.3	13.5	12.4	11.3	10.3	9.8
30	10.4	11.1	12.0	12.9	13.6	14.0	13.9*	13.2	12.4	11.5	10.6	10.2
25	10.7	11.3	12.0	12.7	13.3	13.7	13.5	13.0	12.3	11.6	10.9	10.6
20	11.0	11.5	12.0	12.6	13.1	13.3	13.2	12.8	12.3	11.7	11.2	10.9
15	11.3	11.6	12.0	12.5	12.8	13.0	12.9	12.6	12.2	11.8	11.4	11.2
10	11.6	11.8	12.0	12.3	12.6	12.7	12.6	12.4	12.1	11.8	11.6	11.5
5	11.8	11.9	12.0	12.2	12.3	12.4	12.3	12.3	12.1	12.0	11.9	11.8
0	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0

The last parameter that needs to be determined is the ground heat flux G. This parameter can be assumed to be 0, according to [100].

3.4. Mestelá River Discharge

The discharge of the Mestelá River is an important measure because it is one of the main input values of the hydrological model. Therefore, detailed computation of the river discharge is of utmost importance to guarantee a model that develops trustworthy simulations. The computation of the discharge of the Mestelá River is based on topographic measurements, water level measurements, and multiple water pressure sensors.

3.4.1. River Bathymetry

To analyse the bathymetry of the Mestelá River, a total station from the University of San Carlos was used. This surveying instrument integrates the function of a theodolite with Electronic Distance Measurement (EDM), to measure angles and distances from the instrument to a particular point. The bathymetry of the Mestelá River was measured at two locations, with 5 meters distance in longitudinal direction. Eventually, only one cross-section was used in the computation of the river discharge (Section 3.4). The spacing between each point was 0.25 m.

The coordinates of the cross-section were initially measured in the GTM projection, a local Guatemalan projection. These were later corrected to the standard WGS projection. Additionally, since the measurements were not taken along a straight line, a line was fitted, and the projection was adjusted accordingly. Figure 3.12 illustrates the fitted line through the measurement points. Next, the Haversine formula was used to calculate the distances in meters, which resulted in the final cross-sections. In Figures 3.12 and 3.13, the cross-section is shown.

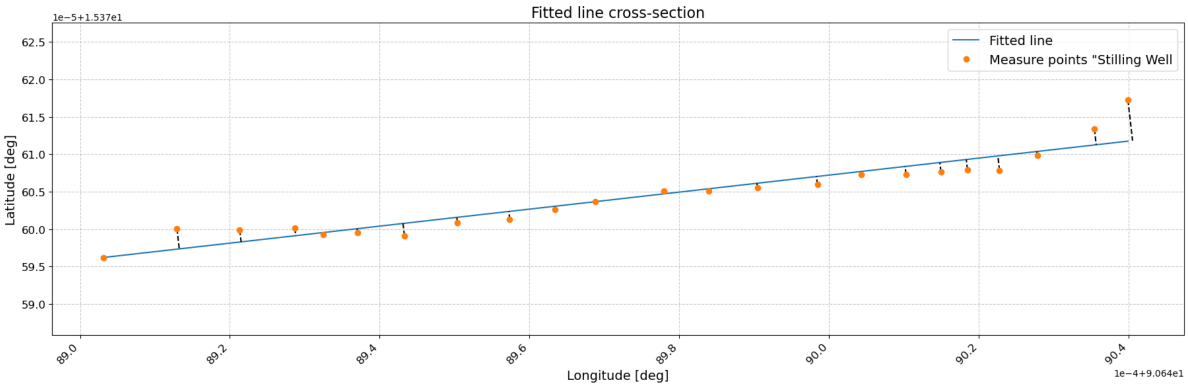


Figure 3.12: In this figure the topographic measurements are shown in longitude and latitude. The fitted lines show how these measurements are projected to form a straight line of the cross-section. This line is then used for the discharge model to calculate certain parameters.

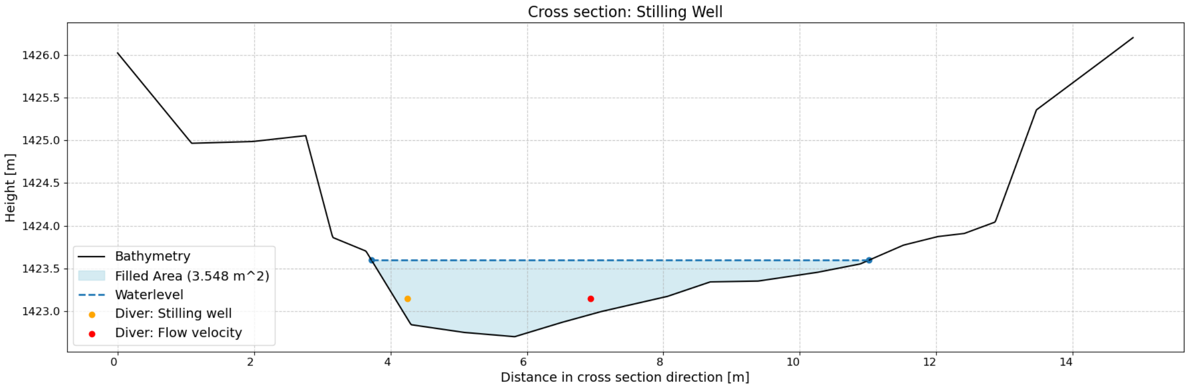


Figure 3.13: Cross-section 2, at the location of the stilling well.

3.4.2. Water Level Measurements

To measure the water level of the river a stilling well was placed. This is a commonly used construction for monitoring surface waters. This stilling well consists of one vertical PVC pipe (400 x 5 cm) connected to a horizontal PVC pipe (200 x 5 cm). In the horizontal pipe, holes are drilled where the water can enter the stilling well. Due to the extra friction in the horizontal pipe and the absence of direct vectors such as flow velocity and wind waves, the stilling well displays the actual water level. In the vertical pipe, a diver (TD-Diver, Van Essen) was placed that recorded and stored the recorded pressure every 15 minutes. Throughout the day, the air pressure can fluctuate with a lower pressure as the air heats up and a higher pressure when it cools down. The diver that measures the water pressure is also affected by the fluctuating air pressure. Therefore, an extra diver is installed on top of the stilling well, which measures the barometric pressure. With both pressures known at each time, the water column above the diver can be calculated with Equation 3.15 [93].

$$WC = (p_{\text{diver}} - p_{\text{baro}}) \tag{3.15}$$

Table 3.5: Parameters of the water column formula, based on the water pressure.

Symbol	Parameter	Unit
WC	Water Column above diver	cm
p_{diver}	Water pressure	cm H_2O
p_{baro}	Barometric pressure	cm H_2O
ρ	Density of water (= 1000 kg/m^3)	kg/m^3
g	Gravitational constant (= 9.81 m/s^2)	m/s^2

3.4.3. Velocity Measurements

To determine the average flow velocity, a diver is placed in the river. It measures the total pressure at that certain point. By comparing this pressure with the pressure from the diver that is placed in the stilling well, the flow velocity at that point can be calculated with Bernoulli's principle. This can be explained by comparing the situation with a Pitot meter, see Figure 3.14.

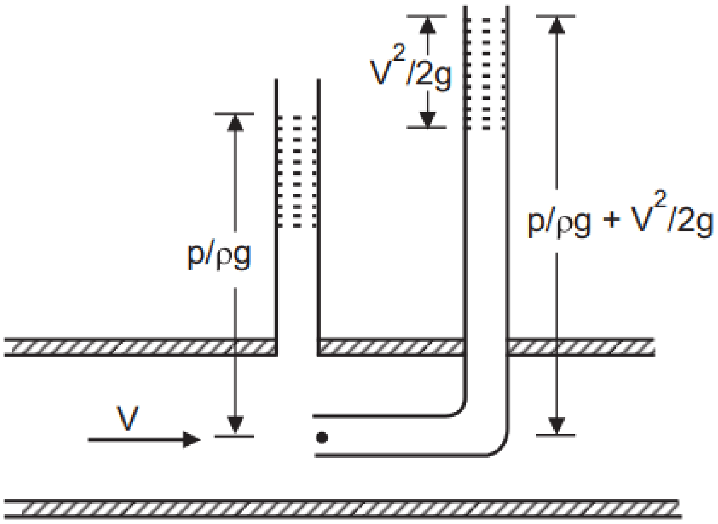


Figure 3.14: Pitot meter, based on the principle of Bernoulli.

The figure shows the difference in hydraulic pressure when the velocity increases. A higher flow velocity results in a higher water column above the second tube. This can be explained when looking at Bernoulli's Principle (Equation 3.16). The total hydraulic pressure equals a constant or another point in the same energy balance. When looking at the system in the river, the stilling well is represented by the first tube and measures the static water pressure. The second tube, represented by the diver in the river, measures to total hydraulic pressure at that point. Both divers are placed at the same height and when assuming there is no velocity within the stilling well, only the velocity in the river is unknown. The formula can therefore be rewritten in the formula of Torricelli (Equation 3.17). Here, the potential energy, represented by the increase in the water column, becomes kinetic energy.

Bernoulli Equation:
$$P_1 + \frac{1}{2}\rho v_1^2 + \rho g h_1 = P_2 + \frac{1}{2}\rho v_2^2 + \rho g h_2 \tag{3.16}$$

Torricelli Equation:
$$v_2 = \sqrt{2g\Delta h} \tag{3.17}$$

3.4.4. Computation River Discharge

The water level in the river is highly fluctuating, which has a large effect on the flow velocity, and thus the discharge of the river. To calculate the discharge as accurately as possible, a hydraulic model is made. This model takes as input the previously mentioned measurements: water level, river bathymetry and measured flow velocity.

Assumptions

In the model, the following assumptions are made. In the river shallow water is assumed, this can also be seen in a cross-section of the river bathymetry, the vertical length scales are much smaller than the horizontal length scales. With shallow water assumed, the advection terms in the vertical direction can be neglected and the water can be seen as hydrostatic.

When looking at the path of the river there are no sudden changes in the bathymetry, therefore the flow in the river is described as a uniform flow. Here, the flow velocity does not change in the stream-wise direction and there are no accelerations and decelerations in the flow direction. The absence of changes in the flow pattern causes the turbulent boundary layer to fully develop, covering the whole water depth. In these uniform flow conditions, the bed shear stress increases linearly, with zero at the water level and maximum near the bed. The bed shear stress has a direct influence on the advection in stream-wise directions and yields a logarithmic vertical velocity profile [97].

Procedure

The logarithmic velocity profile can be plotted as a function of the water depth with Equation 3.18 [3]. In this equation, the shear velocity is divided by the Von Karman constant k and multiplied by the natural logarithm of the vertical height divided by the roughness coefficient z_0.

$$u(z) = \left(\frac{u^*}{\kappa}\right) \cdot \ln\left(\frac{z}{z_0}\right) \tag{3.18}$$

Table 3.6: Parameters of the velocity profile formula.

Symbol	Parameter	Unit
$u(z)$	Stream wise particle velocity at depth z	m/s
u^*	Shear velocity	m/s
κ	Von Karman constant (= 0.41)	-
z_0	Roughness level	m

First, the boundary resistance coefficient c_f is calculated. This dimensionless coefficient characterises resistance in fluid flow over a solid surface based on wall shear stress. There are multiple ways to calculate c_f. In this case, it was decided to base c_f on Manning's coefficient n using Equation 3.19 [3]. By assuming natural river channels with pools and shoals, Manning's coefficient is set to 0.035 $m^{-1/3}s$. The hydraulic radius R is based on the area of the river's cross-section and the wetted perimeter.

$$c_f = \frac{g}{R^{\frac{1}{6}} n} \qquad \text{with} \qquad R = \frac{A_c}{P} \tag{3.19}$$

Table 3.7: Parameters of the equation for the boundary resistance coefficient.

Symbol	Parameter	Unit
c_f	Boundary resistance coefficient	-
g	Gravitational constant (= 9.81 m/s^2)	m/s^2
R	Hydraulic radius	m
n	Manning's coefficient (= 0.035 $m^{-1/3}s$)	$m^{-1/3}s$
A_c	Area cross-section	m^2
P	Wetted Perimeter	m

Second, an iteration needs to be performed to calculate the shear velocity $u(z)$ and u^* simultaneously. As can be seen, the flow velocity $u(z)$ is dependent on the shear velocity u^*, which is again dependent on the depth-averaged velocity. Therefore, an iteration process is required using Equations 3.18 and

3.20 [3].

It is assumed that the depth-averaged flow velocity is equal to the flow velocity at 40% of the water depth. The initial value used for the depth-averaged flow velocity is based on a linear flow-velocity profile. The iteration process is done in such a way that the measured flow velocity corresponds with the modelled velocity.

$$u^* = \sqrt{c_f} * U \tag{3.20}$$

Table 3.8: Parameters of the shear velocity equation.

Symbol	Parameter	Unit
u^*	Shear velocity	m/s
c_f	Boundary resistance coefficient	-
U	Depth-averaged flow velocity	m/s

Third, to determine the average flow velocity for the whole river, the cross-section is divided into small parts Δx. In each Δx the logarithmic velocity profile is modelled and the average flow velocity is calculated. Then, these flow velocities are averaged over the whole cross-section to end up with the cross-sectional average flow velocity.

Finally, the discharge per 15 minutes is computed using the cross-sectional average flow velocity and the area of the cross-section. This data, in combination with the water level, is used to fit the rating curve. The fitted line is based on the power law equation [39], which is given in Equation 3.21. The resulting rating curve is shown in Section 4.4.

$$Q = a \cdot h^b \tag{3.21}$$

Table 3.9: Parameters of the power law equation.

Symbol	Parameter	Unit
Q	Discharge	m^3/s
h	Water level	m
a	Fitting parameter	-
b	Fitting parameter	-

3.4.5. Long-term Measurement Setup

Measurements conducted by the divers were limited to the project's duration as they were borrowed from the Waterlab at Delft University of Technology. To continue measuring the water level after the project's completion, a stage was constructed and installed in the Mestelá River. This, along with the fitted rating curve, enables the measurement of the Mestelá River Discharge post-project. The constructed stage can be seen in Figure 3.15.

Figure 3.15: The installed stage to measure the water level of the Mestelá River.

3.5. FLEX-Topo Model

In this section, the development of the FLEX-Topo model is elaborated upon in detail. First, the Mestelá River catchment is classified based on its landscape. Second, the adaptations of the model are explained. Finally, it is explained how the model is run.

3.5.1. Landscape Classification

The FLEX-Topo model is a conceptual model that bases the hydrological processes on the topography of the catchment. The classification of the landscape of the Mestelá River catchment is based on several basin characteristics. All visualisations of these analyses can be found in Appendix A. The following analyses were used:

- Height Above Nearest Drainage (HAND): Initially, a unique ID was allocated to every raster pixel in the Strahler stream raster. Using the 'Subcatchments' function of the PCRaster plugin and LDD, each unique ID was linked to corresponding subcatchments. This led to the creation of a subcatchment raster that delineated runoff areas for every river pixel. Subsequently, the drainage's elevation was determined as the minimum elevation within each subcatchment. The HAND was then computed by subtracting the drainage elevation from the DEM.
- Slope: The slope was directly derived from the DEM.
- Leaf Area Index (LAI): This index is a commonly used measurement to describe the canopy. It quantifies the layers of leaves of the canopy per square meter. For instance, a canopy with an LAI of 1:1 has only one leaf layer per square meter, while a canopy with an LAI of 3:1 has three leaf layers per ground square meter [14]. To determine the LAI, Sentinel-2 data of the catchment is analysed with the SNAP plugin in QGIS, which uses an algorithm developed by the European Space Agency (ESA). The Copernicus Sentinel-2 mission comprises two polar-orbiting satellites to monitor the variability in land surface conditions [27]. The satellites send out different bandwidths of light (15 μ_m up to 175 μ_m), with a high-resolution pixel size of 10 to 60 meters, which measures how much light is reflected. With the ratio of reflected light different indexes can be calculated, such as the Normalised Difference Vegetation Index (NDVI) and the Normalised Difference Water Index (NDWI), and with the SNAP plugin the LAI is calculated. All the sentinel data can easily be downloaded from the Sentinel EO browser. For this research, the data file of 04-04-2023 is chosen as this date has a cloud coverage of 0.0% over the catchment area. For this analysis, a pixel size of 10x10 m was initially used but was resized to 30x30 meters for compatibility.

- Spectral analysis: A spectral analysis was used to validate the find patterns in the catchment, of which the code can be found in Appendix A. The analysis was done using Landsat 8 data with bands 1 up to 7. The classification was executed with the ‘Semi-Automatic Classification Plugin’ in QGIS. With the use of a training set, three general categories were found within the catchment: Agriculture, Plantation and Cloud Forest. Validation of these categories was done with Tara de Vries, one of the directors of CCFC who has lived in the area for over twenty years. The results, which can be found in Appendix A were used as a visual basis upon which the LAI and HAND will be changed.

The definition of the classes of the FLEX-Topo model are not the same as the classification of the spectral analysis, as the model classes are based on different conditions as the spectral analysis. The model classes are defined by changing the values of the LAI and the HAND and matching it with the result of the spectral analysis. Thresholds of 8 meters for HAND and 1.8 for LAI were found satisfactory. With these thresholds, Agriculture contains 45% of the catchment, (cloud) forests 44% and low drainage areas 11%. The resulting classification is displayed in the Figure 3.16. The code used for the classification can be found in Appendix A.

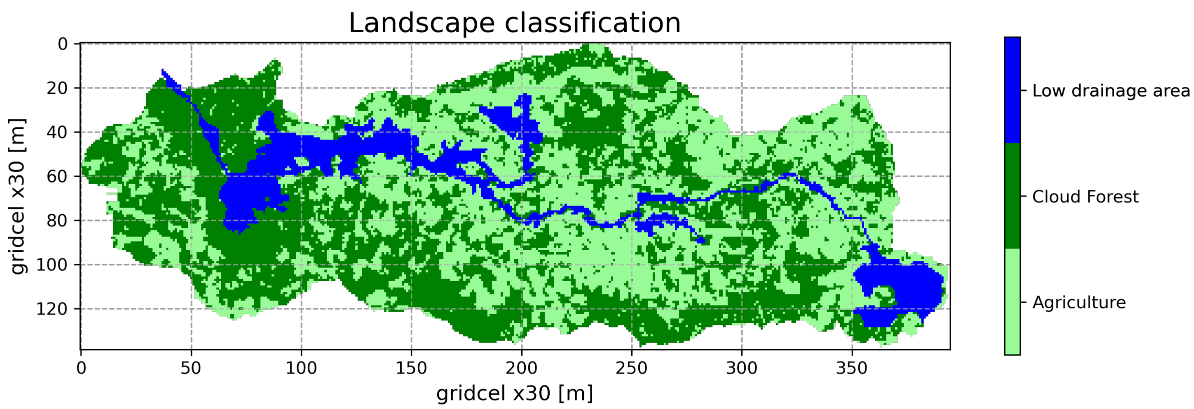


Figure 3.16: Landscape classification of the Mestelá River catchment, with low drainage areas being indicated in blue, (cloud) forests in dark green and agriculture in light green. The result of the landscape classification is used to set up the FLEX-Topo model.

3.5.2. Adaptations

The framework and code for the FLEX-Topo model are based on the 2023 ENVM1502 lecture at Delft University of Technology. Some adaptations were performed such that the model matches the Mestelá River catchment and its hydrological processes the best. Initially, the model contained three classifications:

1. Plateau: HAND > 5 meter and slope < 11 degrees.
2. Hillslope: HAND > 5 meter and slope > 11 degrees.
3. Low drainage area: HAND < 5 meters and no restriction on slope.

The FLEX-Topo model bases its classification on HAND and slope. In this case, the landscape classification is based on HAND and LAI instead, because only a small portion of the catchment has a low slope. This resulted in the initial class of hillslope being used as a basis for the modified classes Cloud Forest and Agriculture. The initial class Low drainage area is unaltered in the model structure. The modified class Agriculture is only altered in name, the model structure remains the same. However, Cloud Forest has been modified to fit the dynamics of the system better. These modifications will be explained in the following paragraph. All fluxes, states and parameters are shown in both Figure 3.17 and Appendix B.

Cloud forest structure alterations

The goal of the model is to simulate the processes occurring within cloud forests in the catchment. In addition to the processes already defined within the FLEX-Topo framework, the processes that the model should mimic include condensation and moisture release from epiphytes and mosses. All parameters, including those newly added to the structure, are described in Table 3.10. The following modifications have been made to the model to reproduce these processes:

- Horizontal precipitation only occurs when a cloud is pushed up against a mountain, or when the relative humidity exceeds the saturation threshold, and condenses. Since our model does not include orographic influences and cloud travel, we focused on the condensation in the system. How this process is calculated is explained in Section 3.5.2. In the model structure, the condensation is added as the flux P_h, that enters the interception bucket in class Cloud Forest.
- Two new parameters were introduced to mimic the buffer release from the interception bucket: $S_{i,min}$ and $K_{i,BR}$. The parameter $S_{i,min}$ is intended as a threshold, below this threshold no buffer release occurs. If the volume in the interception bucket is above this threshold, water will slowly leak with the volume above this minimum threshold, times the factor $K_{i,BR}$. This parameter $K_{I,BR}$ is an arbitrary parameter that will be calibrated. The volume that "leaks" is added to the throughfall (P_e).

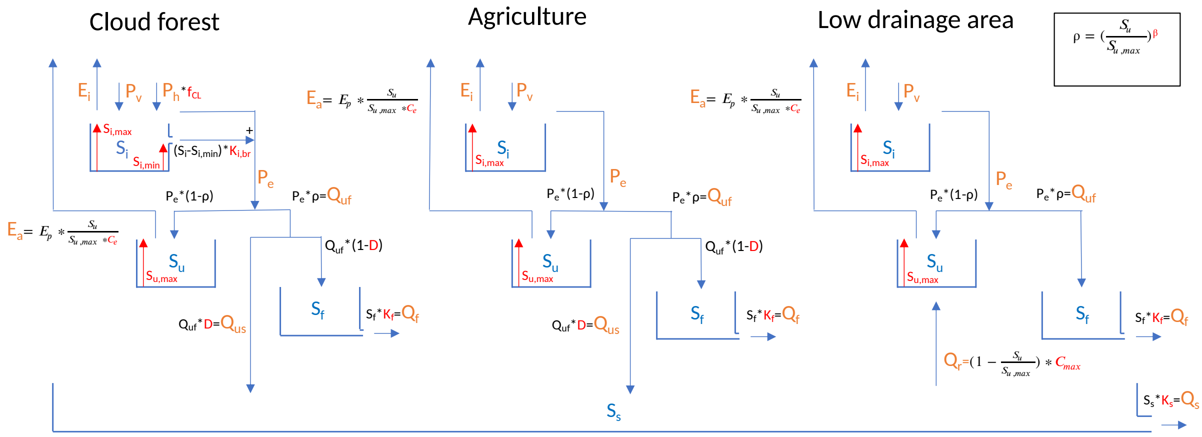


Figure 3.17: Modified FLEX-Topo flowchart. The fluxes are indicated in orange, the states in blue, and in red the parameters that can be adjusted.

Table 3.10: Quantification and description of the parameters used in the FLEX-Topo model.

Parameter	Description	Unit	Low drainage area	Agriculture	Cloud Forest
f_{CL}	Coefficient for evaporation recycling	-	0-0.4		
K_s	Baseflow recession coefficient	-	0.0000005-0.0000200		
T_{lag}	Weighting function for modelled discharge	60/15min	72-288		
C_e	Evaporation coefficient	-	0.1-0.9	0.1-0.9	
$S_{u,max}$	Maximum water storage in unsaturated bucket	mm	10-150	5-100	
β	Coefficient for throughfall distribution	-	0.2-5	0.6-6	
C_{max}	Recharge coefficient	-	0.02-0.8		

Table 3.10: Continued from previous page

Parameter	Description	Unit	Low drainage area	Agriculture	Cloud Forest
K_f	Fast flow recession coefficient	-	0.00002-0.00009	0.00002-0.00015	
I_{max}	Maximum water storage in interception bucket	mm	6-28	4-20	7-40
I_{min}	Minimum water storage in interception bucket	mm			1-4
D	Distribution coefficient for overland flow or groundwater infiltration	-		0.2-0.9	0.6-0.99
$K_{i,BR}$	Epiphytes and mosses buffer release coefficient	-			0.0002-0.03

Moisture buffer release

The typical epiphytes in a cloud forest are mosses, orchids and bromeliads. These epiphytes contribute to the storage and slow release of accumulated water on the tree. To simulate this release of water into the system, the same system as snow release is used. In this system, a threshold temperature is used, above which water stored as snow starts to melt and is added to the unsaturated bucket. Only volume above the threshold of I_{min} can leak out of the interception bucket. The factor with which it leaks is the $K_{i,BR}$. The resulting formula can be found in Equation 3.22.

$$\text{Moisture}_{\text{buffer release}} = (S_i - S_{i,min})K_{i,br} \tag{3.22}$$

Mist condensation

During the late night and early morning hours, as temperatures continue to decrease, the air's ability to retain moisture also decreases. This reduction in the air's water-holding capacity is illustrated in the psychrometric chart provided in Appendix E. When the relative humidity reaches its maximum level, the air is saturated with moisture. Subsequent cooling of the air leads to the condensation of water vapour onto epiphytes, mosses and plants. This condensation of water can be quantified through the change in specific humidity (also called humidity ratio). Specific humidity is expressed as the weight of water vapour in kilograms per kilogram of air [78] and is presented in Equation 3.23. The related parameters are explained in Table 3.11.

$$q = 0.662\frac{e_a}{p} \tag{3.23}$$

The calculation of the actual vapour pressure (e_a) relies on Equation 3.9, which requires the saturation water vapour pressure determined by Formula 3.9 as an input. As the model is designed to work with input data in millimetres per square meter (mm/m^2), the horizontal precipitation in the form of mist condensation should also be expressed in the same unit. By analysing the change in the humidity ratio, we can determine the quantity of water vapour in kilograms per cubic meter (kg/m^3) that has condensed within the system. To convert this ratio into a weight, the density of humid air should be considered, which can be computed using the following formula:

$$\rho_{humid} = \frac{\rho_{dry}(1+q)}{1+1.609q} \quad \text{with} \quad \rho_{dry} = \frac{p}{R_a \cdot T} \tag{3.24}$$

It is assumed that the average tree height in the cloud forest is 8 meters. 8 m^3 volumes of air, stacked on top of each other results in a weight [kg], which can be converted to volume [L], which is the same as mm/m2 in the case of water. This flux will be added in the model to the class Cloud Forest as horizontal precipitation. Horizontal precipitation in the model only occurs when the temperature in the previous

Table 3.11: Parameters for the mist condensation formulas.

Symbol	Parameter	Unit
q	Specific humidity	-
e_a	Actual vapour pressure	Pa
p	Pressure	Pa
R_a	Gas constant of dry air	J/(kg K)
RH	Relative Humidity	%
T	Temperature	K
ρ_{humid}	Density humid air	kg/m^3
ρ_{dry}	Density dry air	kg/m^3

time step is higher than the temperature in the current time step and the relative humidity is larger than 99%.

3.5.3. Model Run

In hydrological models, timesteps are commonly 1 day. In this case, the FLEX-Topo model is run in both a 15-minute time step, to match the measurement time of the river discharge, and a 1-hour time step. The same simulation technique was applied for both time steps. For all 19 parameters, a minimum and a maximum value were taken. Between this minimum and maximum value, a sampler of uniform type was used as a parameter input for the FLEX-Topo model. The model run that for the 1-hour time step utilised 500,000 parameter sets, while the 15-minute time step used 1,000,000 sets. The goodness of fit between the simulated and measured discharges was determined with an objective function using the Nash-Sutcliffe-Efficiency (NSE) coefficient.

3.6. Stakeholder Management

3.6.1. Research Design

1. **Qualitative Interviews**
   Conduct semi-structured interviews with a diverse group of respondents to explore their experiences, perspectives, strategies and challenges related to the cloud forest ecosystem. During the project, plenty of interviews were conducted to get interaction with various respondents. An overview of the main challenges and strategies they experienced resulted from the interviews.
2. **Story analysis**
   Analyzed the qualitative data collected from interviews using open coding, axial coding, and selective coding methods. Categorized challenges, issues, and strategies identified in the interviews. The analysis aimed to uncover patterns, themes, and dependencies within the collected data. Through this method, challenges experienced by different respondents were linked to a certain challenge category and stakeholder engagement strategy category.
3. **Construct the framework**
   Developed stakeholder engagement strategies for CCFC. Based on the insights gained from qualitative interviews and story analysis, formulated a range of stakeholder engagement strategies. These strategies were designed to address the identified challenges, align with stakeholders and their concerns, and cater to the specific context and objectives of CCFC.
4. **Translating it into action**
   Worked collaboratively with CCFC to translate one of the stakeholder engagement strategies into actionable steps and initiatives. Ensured it aligned with CCFC's goals and the broader community's needs. The insights derived from the interview analysis were instrumental in selecting and developing the most appropriate interventions. The interventions were based on the strategies and ideas mentioned during the interviews, ensuring that the challenges collected during the interviews were covered, thereby trying to maximise their impact and effectiveness. The chosen interventions were chosen to cover needs in CCFC's operations. Additionally, recommended a monitoring program to track the success and intended impact.

By achieving these objectives, the research aimed to conduct a thorough qualitative analysis of the challenges encountered by stakeholders within the cloud forest ecosystem. This analysis would enhance our comprehension of ecosystem dynamics and stakeholder interactions, facilitating the formulation of effective stakeholder management strategies. Ultimately, these efforts would benefit both CCFC and the various stakeholders connected to or impacted by the cloud forest ecosystem, as the research findings were translated into practical/tangible initiatives.

3.6.2. Method: Qualitative research

For evaluating this research objective, a qualitative research approach was used. With a qualitative research approach, an in-depth understanding of the challenges experienced and strategies used by stakeholders and other relevant actors was gained. A qualitative approach was suitable for exploration and interpretation, which was needed for this research objective [40].

3.6.3. Data collection: Interview

A qualitative approach to data-gathering was the most suitable. Therefore, data collection was done through conducting interviews. Interviewing was a qualitative research method that involved engaging in direct, interactive conversations with participants to gather in-depth and rich data and gain insights into their experiences, perspectives, and knowledge [52, 47]. The goal of these interviews was to identify current strategies and challenges experienced by stakeholders and other relevant actors.

The interviews were in the form of semi-structured interviews. Semi-structured interviews were perfect for ensuring a systematic process while allowing flexibility for participants to share their perspectives and experiences [52]. The goal was to have around 15 interviews. The selection of respondents had a wide variety to get a full picture of the challenges and strategies currently experienced and used. It was important that all different sorts of relevant actors were included: clients, environmental organizations, local residents, etc.

The interview contained about 10 open questions regarding or coupled with the Cloud Forest ecosystem of the area and the issues surrounding that.

Limitations

Interviews can have some limitations. One important risk of this form of data collection and research is the possibility of subjectivity and bias in the collected qualitative data. This includes the biases of the one conducting the research as well as the biases of the participants. The bias of the one conducting the research can have an influence on assumptions and interpretations. Because the researcher will interpret the data from the interview as well as will set up the interview. Therefore it is important to be reflexive as a researcher. Also, the possibility of subjectivity in the answers from the participants needs to be taken into account. As for practical limitations, the research design suggested here is time and resource-intensive. Allocation of sufficient time is therefore important as also to be aware of the fact that there is access needed to the different stakeholders [53].

Conducting interviews with external stakeholders can lead to difficulties. They do not have a direct interest in the project, which means that it can be difficult to bring these stakeholders on board. Conducting interviews it is important to be mindful of the varying levels of knowledge among participants. Some stakeholders may have a deep understanding of the subject matter, while others may have limited knowledge. Tailoring questions and explanations to the participants' knowledge levels is therefore important.

Especially in this research, the diverse group of stakeholders can lead to language barriers which impede effective communication. A translator will be used to conduct the interviews. Also, cultural differences can significantly impact communication and interpretation during interviews. It is therefore important to be sensitive to cultural differences and employ culturally competent approaches to ensure respectful and meaningful interactions.

3.6.4. Analysis

Interviews were conducted to gather insights into the challenges faced and strategies employed by various stakeholders and other relevant actors. To analyze the qualitative data collected, the grounded theory method was used. Grounded theory involved a multi-step process, including open coding, axial coding, and selective coding. This method was used to develop a tailored stakeholder management framework for the NGO CCFC based on the data gathered from the interviews.

For analysing the collected qualitative data, the first step was open coding. Open coding broke down the data collected from the interviews into discrete parts which were referred to as "mini-stories". Open coding made it possible to deconstruct the collected data. The goal was to accumulate around 30 mini-stories. Following up the open coding was axial coding. The aim of axial coding was to identify connections between the mini-stories developed with open coding. By using axial coding, the mini-stories were organized into challenge categories. The challenge categories emerging from axial coding were derived from the data and were not predetermined. The final step was selective coding. Selective coding aimed to find key categories that interlinked and harmonized the categories from axial coding. The selective coding categories were the proposed stakeholder engagement strategies for CCFC, to adopt for solving the challenge categories of the axial coding. Figure 3.18 illustrates the coding pattern. This analysis helped to uncover patterns, themes, and dependencies within the collected qualitative data [71].

This process resulted in a stakeholder management framework designed to align with the challenges presented by stakeholders and other relevant actors and the objectives of CCFC. Doing this analysis resulted in bridging the gap between stakeholder needs and CCFC's practices, resulting in a practical and tailored stakeholder management framework that enhanced the organization's ability to meet its conservation goals while addressing the concerns and needs expressed by the stakeholders involved in or affected by the cloud forest ecosystem.

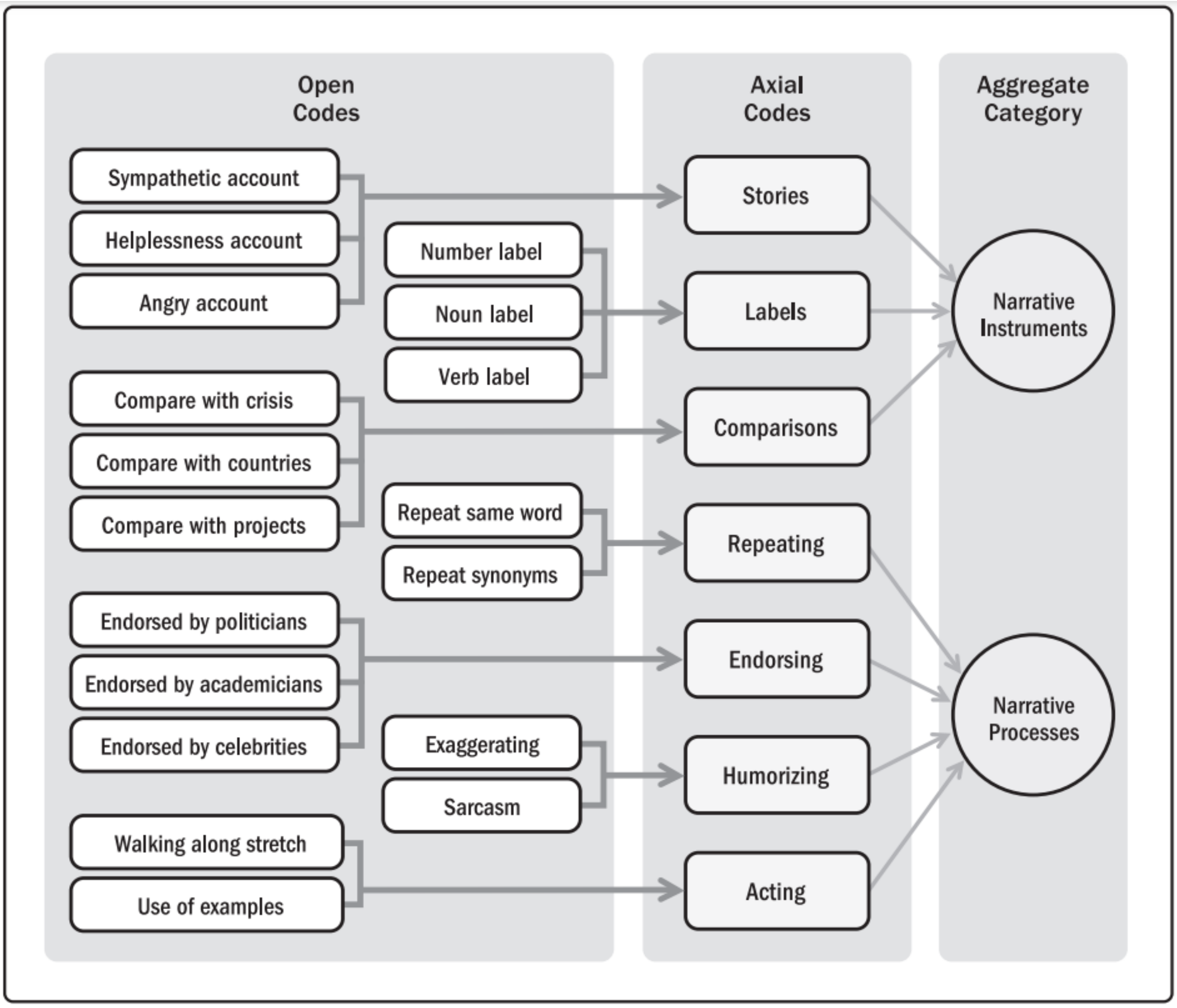


Figure 3.18: Coding [65]

4 Results

In this Chapter, the results of the MDP project are elaborated upon. First, the construction of the long-term measurement site is reviewed. Second, multiple parameters related to some hydrological processes are plotted. Third, the data of the Mestelá River discharge is shown, in combination with the fitted rating curve. Then, the output of the FLEX-Topo model is shown, in combination with the measured data. Finally, the stakeholder framework is presented.

4.1. Long-term Measurement Site

A substantial part of the results related to the measurement site are presented in Section 3.3 because the construction of the setup was the main objective. In extension, the goal is to establish a station that will provide long-term measurements in the future. To guarantee this, multiple considerations needed to be made. Firstly, the power supply should be sufficient at all times. In the setup, this is done by using a solar panel. During the project duration, the battery of the HOBO station was between 84 and 90 %. Next, the internet connection should be sufficient to provide data transmission, this also resulted in no problems. Data accessibility is also important; the data will be presented on the HOBO-link website, which will be accessible for CCFC. Moreover, the maintenance will be done by CCFC. In this way, the long-term measurement station is established.

4.2. Interception and Storage of Epiphytes

As described in Section 3.3.2, the interception and storage capacity of non-vascular epiphytes can be determined through two types of experiments: storage capacity and evaporation. While the evaporation experiment was executed and its results are presented in Figure 4.1, the storage capacity experiment was not conducted, which is further discussed in Section 5.2.3.

The evaporation experiment, spanning approximately 4 days, involved linear interpolation between data points to illustrate the evaporation pattern. The starting weight of the epiphyte was 103 grams, the end weight was 69 grams. The results indicate higher evaporation rates during the day compared to the night, with greater rates at the experiment's outset, as can be seen in Figure 4.1.

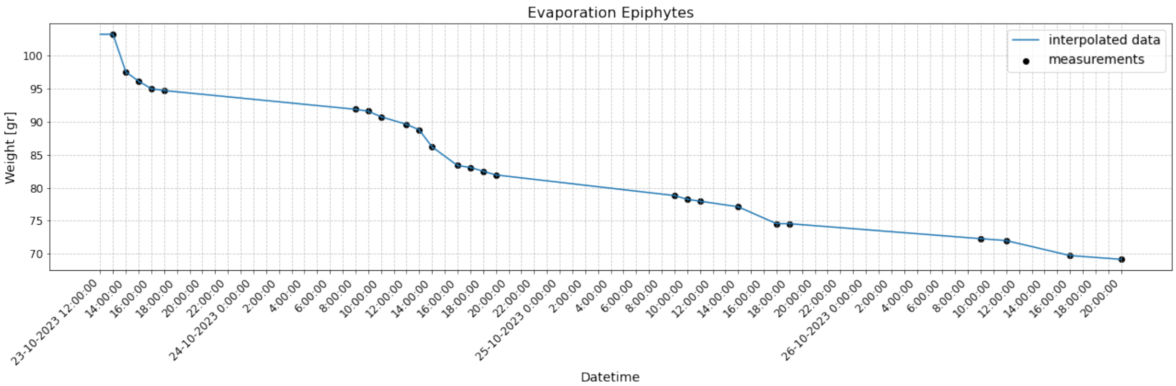


Figure 4.1: Evaporation of water in epiphytes indicated by the difference in weight of the epiphyte in grams. The measurement points are indicated in black, and the interpolation is in blue. The starting weight of the epiphyte was 103 grams.

4.3. Evaporation, Relative Humidity and Temperature

Potential Evaporation

The potential evaporation is calculated with the Penman-Monteith formula, as described in Section 2.3. In the top plot of Figure 4.2, the potential evaporation is plotted from the 10th of October until the 22nd of October. In the plot, the daily potential evaporation varies between 0 at night and a maximum of 0.200 mm on the 11th of October. The data of the potential evaporation during the time frame is stored in the forcing file and used for the FLEX-Topo model (see Section 4.6 for further details). During the night, the temperatures are relatively low, there is no or little solar radiation or evaporation. During the day there can be seen some peaks and dips in the evaporation rate. This can be explained by the varying relative humidity, temperature and solar radiation during the day, which is shown in the plots below the potential evaporation in Figure 4.2. When the relative humidity is high, the air is already highly saturated and can not take up a lot of extra water, therefore the potential evaporation is also lower.

Relative Humidity

The relative humidity is defined as the ratio between the water vapour in the air and the maximum saturated water vapour for that temperature. This ratio is expressed in percentages and is measured at the local weather station (ICOBN4). In this research, the relative humidity is used to calculate the potential evaporation and to calculate the specific humidity, which is used to determine the amount of condensation. Both these calculated parameters are used in the FLEX-Topo model as forcing data. The measured relative humidity is shown in the middle plot of Figure 4.2. It can be seen that the relative humidity is often at a maximum during the night. This can be explained when looking at the temperature plot in the same figure. Here you can see that the temperature drops in the night and the air molecules cool down. This results in less vibrant molecules and a lower dew point, therefore, the air can take in a lower amount of water vapour.

Temperature

The temperature is measured at the local weather station (ICOBN4) as well. In Figure 4.2, in the lowest plot, the temperature is shown for the whole time frame. Here you can see the temperature ranges from the lowest point of 11.5°C at night and a maximum of 30°C during the day. Next to that, the total figure shows a clear correlation between the relative humidity and the temperature, which was already described in Section 4.3.

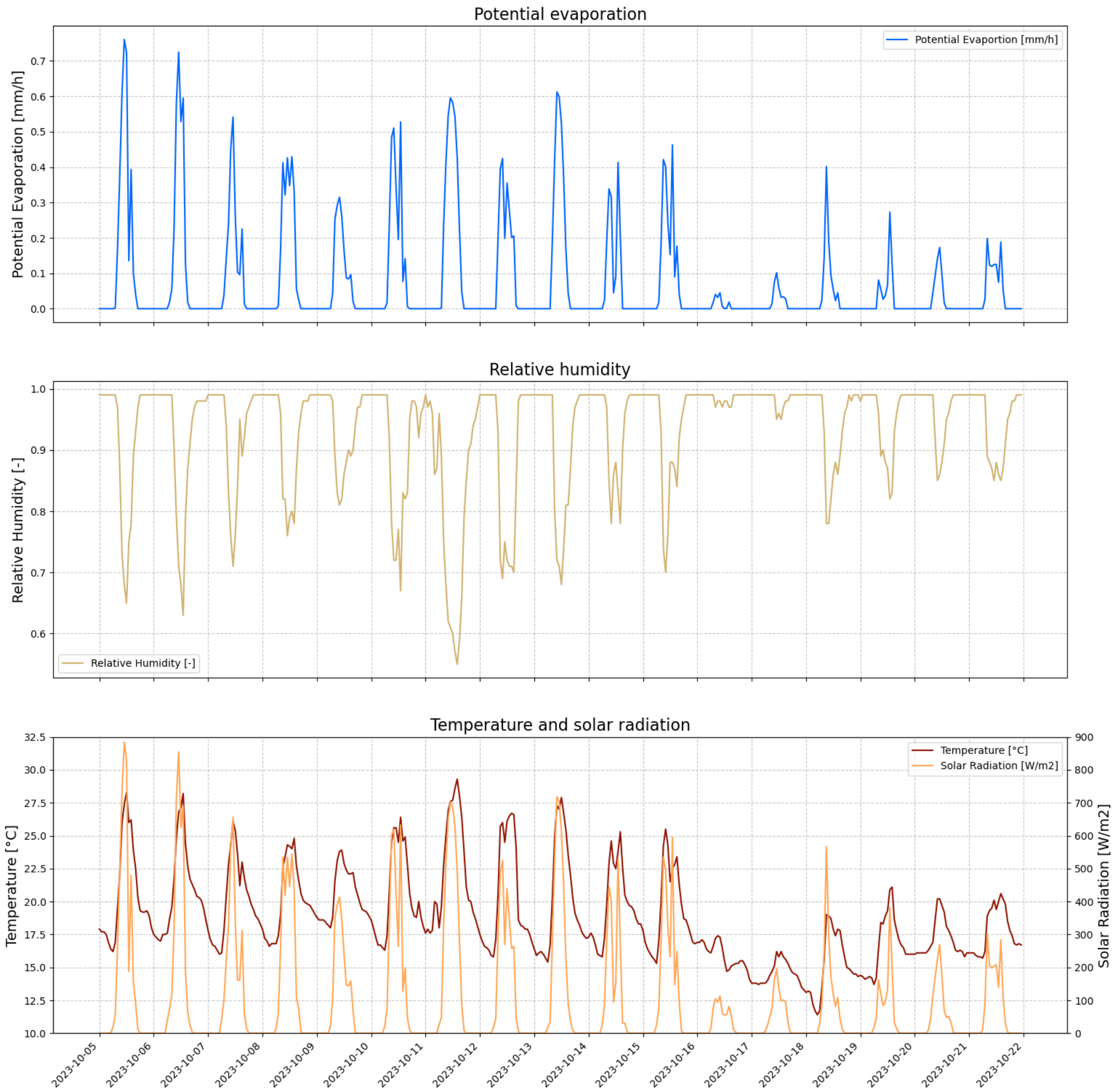


Figure 4.2: Three plots of the potential evaporation (top), the relative humidity (middle), and temperature and solar radiation (bottom). The plots are based on the data retrieved from the local weather station (ICOBN4)

4.4. Mestelá River Discharge

In this Section, the results of the computation of the Mestelá River discharge are presented. Figure 4.3 shows the discharge over time, starting on the 5th of October and ending on the 21st. The range of the discharge is between 4.5 and 10.5 m^3/s. One distinguished peak in the discharge can be seen, of about 10.5 m^3/s, which occurred on the night from the 17th of October to the 18th.

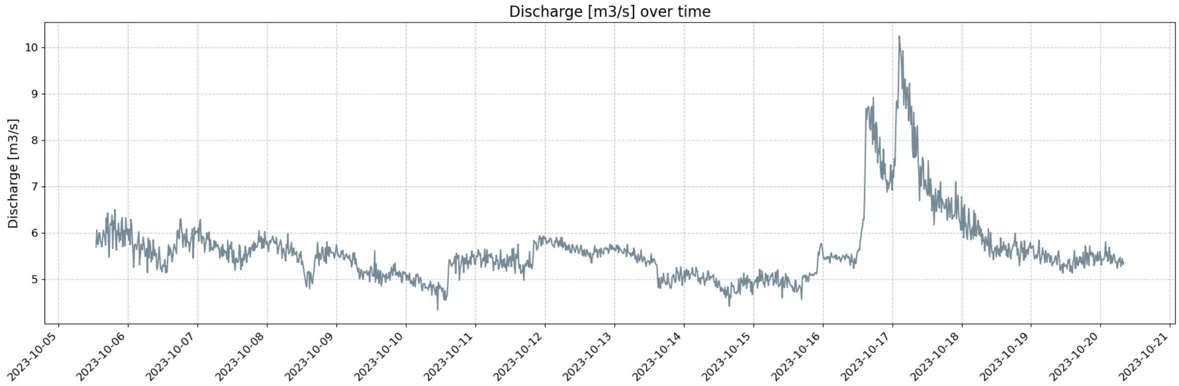


Figure 4.3: Computed discharge of the Mestelá River over time, starting on 05-10-2023 and ending on 21-10-2023.

Based on the discharge computation, the rating curve is computed. The relation between the discharge and the water level is based on the power law. The resulting relation is shown in Equation 4.1. To create the rating curve, a logical data point is added. Namely, at a water level of zero meters, the discharge is assumed to be zero as well. The fitted rating curve and the data points are presented in Figure 4.4.

$$Q = 5.127 * h^{2.360} \tag{4.1}$$

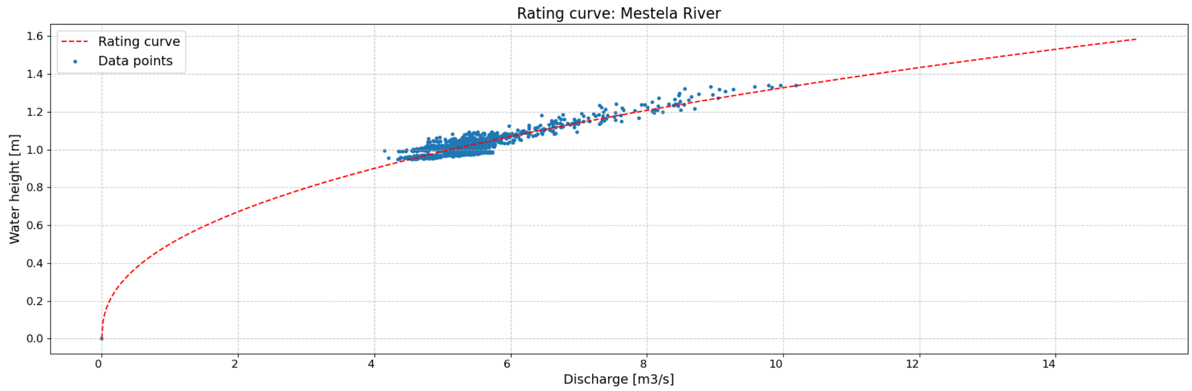


Figure 4.4: Rating curve of the Mestelá River, plotted with the power law described in Equation 4.1.

The variation in the data is indicated with error bars in Figure 4.5. The variation in water height is based on the accuracy of the diver, which is 0.02 meters [93]. And the variation in discharge is based on the accuracy of the computations, which is heavily influenced by the assumptions made. Therefore, this variation is based on 10% of the river discharge.

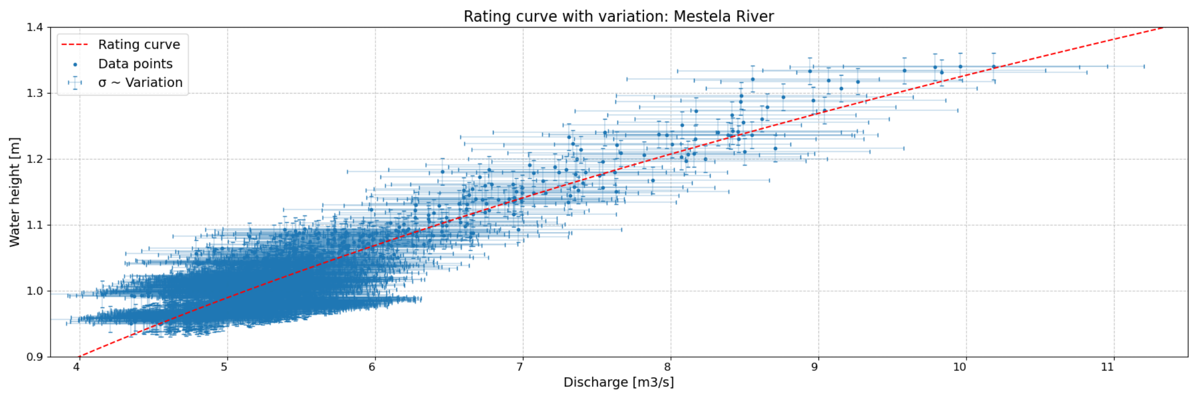


Figure 4.5: Rating curve of the Mestelá River including the variation in water level (0.02 m) and the river discharge (10%).

4.5. Rain and Fog Events

In this Section, rain and fog events in the measured time frame are further analysed. First, the rain and fog events are put into relation to the Mestelá River discharge. Second, both events are used to describe moisture recycling occurring in the cloud forest.

Impact on the Mestelá River Discharge

As discussed in Section 4.4, the Mestelá River discharge exhibited a prominent peak within the measurement period. The upper plot in Figure 4.6 illustrates that the primary driver of this peak is the vertical precipitation data. About 28 hours before the peak in the river discharge, a maximum in the vertical precipitation can be seen. For most of the next 24 hours, it kept on measuring vertical precipitation at the water station. Another result that can be seen in the upper plot of Figure 4.6 is one prominent peak in the vertical precipitation of about 38 mm, on the 12th of October. However, this peak did not influence the Mestelá River discharge, this will be further discussed in Section 5.2.2 of the discussion.

In the lower plot of Figure 4.6 the horizontal precipitation and the computed discharge are plotted. The figure shows little relation between the horizontal precipitation and the Mestelá River discharge peaks. For example, on the 13th of October, despite a peak in the interception of the fog traps, there is no increase in the river discharge for another 2 days. Next to that, the tipping bucket of the fog traps was clogged between the 14th and the midday of the 17th of October. This resulted in 6 days of fog measurements for a total of 17 days.

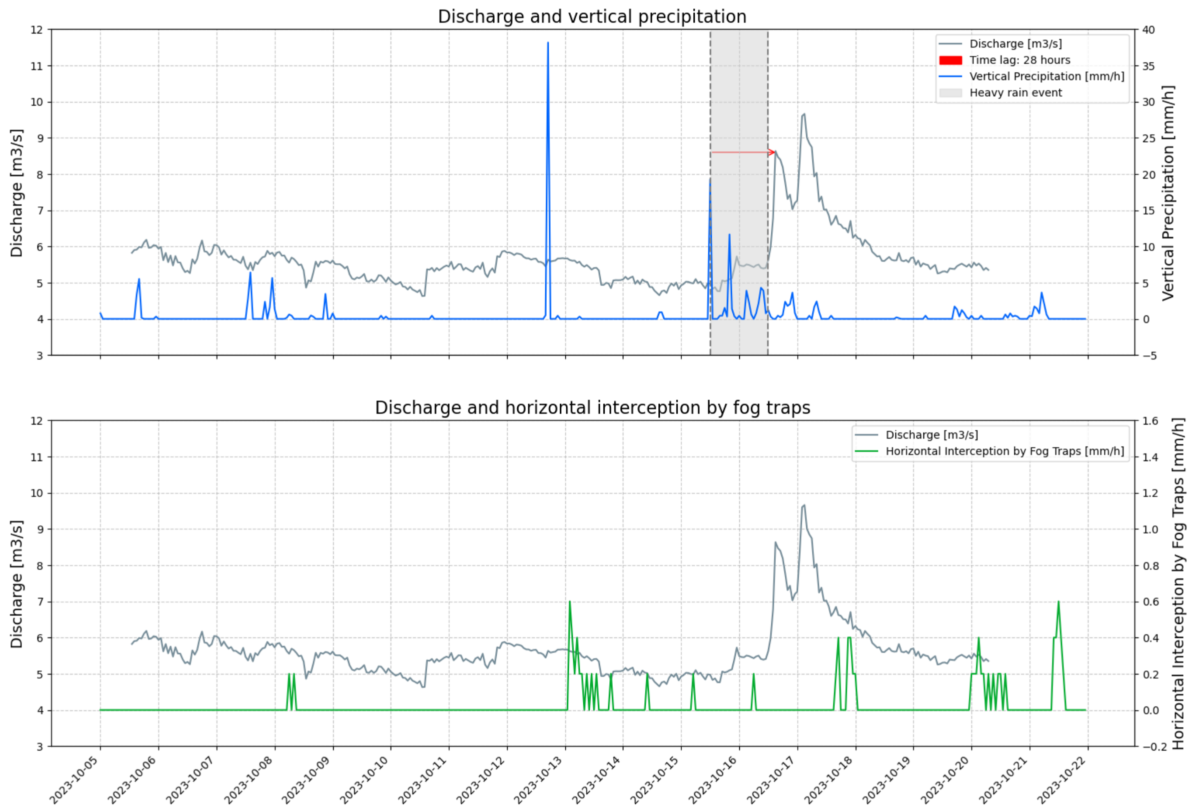


Figure 4.6: The Mestelá River discharge and the vertical (blue, upper plot) and horizontal (green, lower plot) precipitation, in the period between 05-10-2023 and 22-10-2023. Between 14-10-2023 00:00 and 17-10-2023 12:00, the tipping bucket of the horizontal precipitation measurements was clogged.

Timing of rain and fog events

The data collected at the long-term measurement station also showed a relation between the timing of rain and fog events. This analysis involved comparing the moment of occurrence of rain events and fog events. In this case, the rain events are indicated using the throughfall measurements, as it is measured at the same location as the horizontal precipitation measurements, making the timing of the rain and fog events as accurate as possible. The analysis, depicted in Figure 4.7, shows that fog interception often occurs immediately following heavy rain events. Several explanations could account for this phenomenon. Clouds from the rain event may be intercepted by the fog traps, requiring time to saturate before dripping, which results in the tipping buckets recording fog interception. Another possibility is that rain intercepted by the canopy evaporates and then condenses, resulting in fog interception. This post-rain evaporation process is depicted in Figure 4.8. While it may appear contradictory due to the simultaneous evaporation and condensation, the dynamic nature of a cloud forest, characterised by rapid fluctuations in relative humidity and temperature, could make this possible. However, further research is needed to draw definitive conclusions.

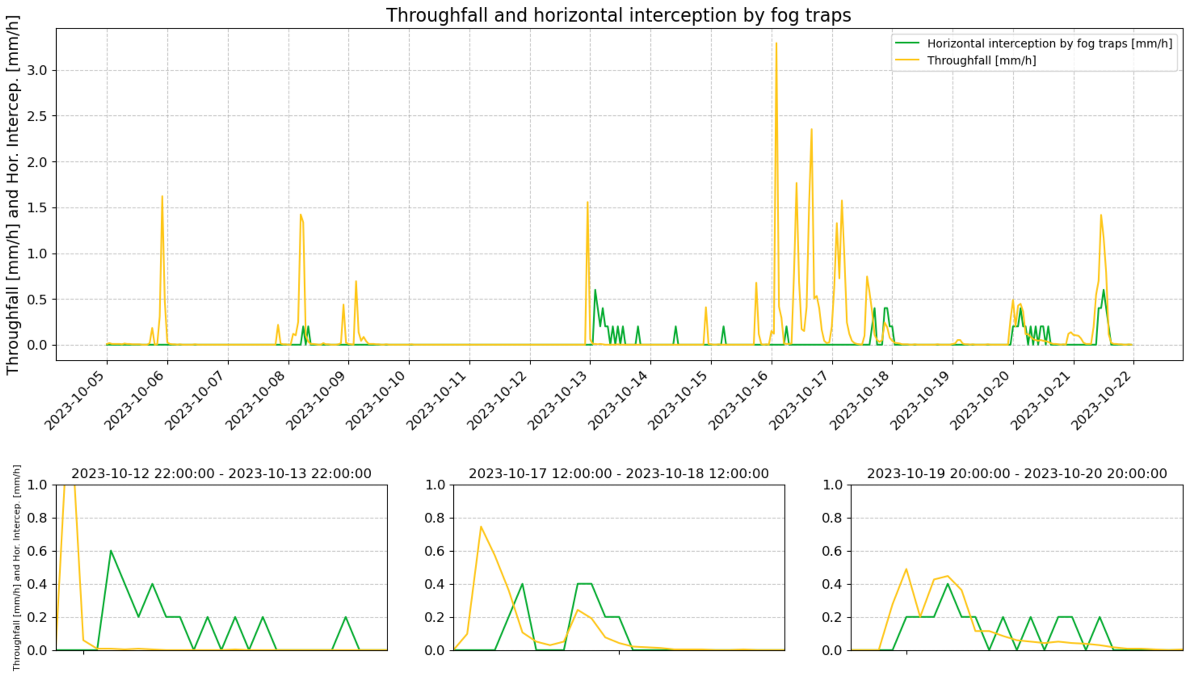


Figure 4.7: The relation between the measured throughfall (yellow) and the horizontal precipitation (green). The lower three plots present in more detail the time lag after a heavy rain event.

Figure 4.8: The evaporation of moisture from the forest canopy after a heavy rain event. *Picture taken on 17/10/2023 at Rubel Chaim*.

4.6. FLEX-Topo Model

This section presents the results of the developed FLEX-Topo model, explaining horizontal precipitation, the simulated buffer release and the modelled discharge of the Mestelá River. Next, the parameters that were simulated in the model are further discussed.

4.6.1. Modelled data

The FLEX-Topo model was executed four times in total: twice with a 15-minute time step, in which one used altered forcing data. And twice with a one-hour time step, also varying with altered forcing data. These alterations were made to account for an outlier in the precipitation data, as explained in Section 4.5. This outlier was associated with a localised rainfall event that occurred on October 12th at the measurement station, with no other nearby stations detecting any rainfall that day. These two altered scenarios are run to check whether the model would respond better to the removal of the outlier.

Horizontal precipitation and buffer release

The model results indicate an overestimation of horizontal precipitation with the current dynamics. In the unaltered fifteen-minute run, the total accumulated horizontal precipitation of the data series is 134.78 millimetres, whilst that of the precipitation is 159.05 millimetres. Indicating that the eight-meter multiplication done in Section 3.5.2 is overdimensioned. The model does capture the expected real-world observations that the timing of the mist condensation is in the night and early morning. This matches the result from the site. As can be seen in Figure 4.10, on the 12th of October a peak of mist condensation occurs. This peak is due to a sudden temperature drop in combination with an already high level of relative humidity.

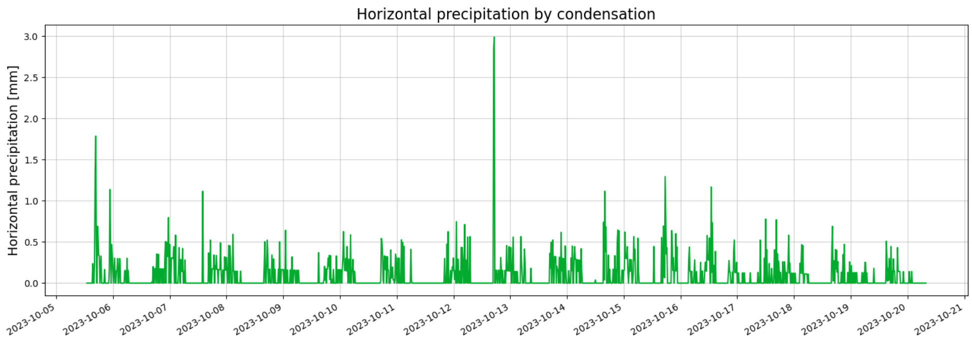


Figure 4.9: Horizontal precipitation simulated in the class Cloud Forest in the 15-minute unaltered run.

Figure 4.10 shows the moisture buffer release simulated by the hydrological model. As can be seen, the moisture buffer release from the interception bucket is in the range of 0 to 0.5 millimetres. Moreover, the release occurs almost continuously, indicating that I_{min}, the minimum water storage in the interception bucket, is seldom reached.

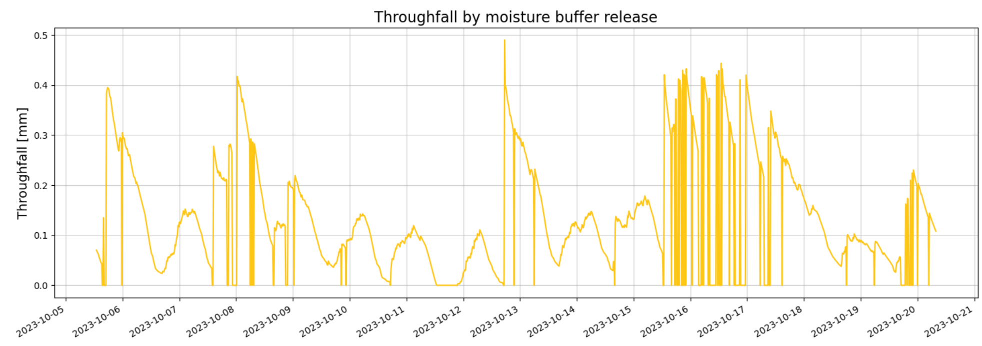


Figure 4.10: Moisture buffer release in the class Cloud Forest on the unaltered 15-minute run.

Modelled discharges

In this Section, the modelled discharge of the FLEX-Topo model is presented and elaborated upon. First, the modelled data of the 15-minute timestep is discussed, which is shown in Figure 4.11. Second, the one-hour run is explained using Figure 4.12. Finally, some general notes about the results are given.

The 15-minute run shows heavy attenuation, as can be seen in Figure 4.11. This is particularly evident in the case of the run with unaltered forcing, where the discharge does not respond to day-long rain events. This indicates that the model has sufficient interception storage to attenuate peak discharges resulting from smaller rain events. However, the runs inadequately capture larger rain events.

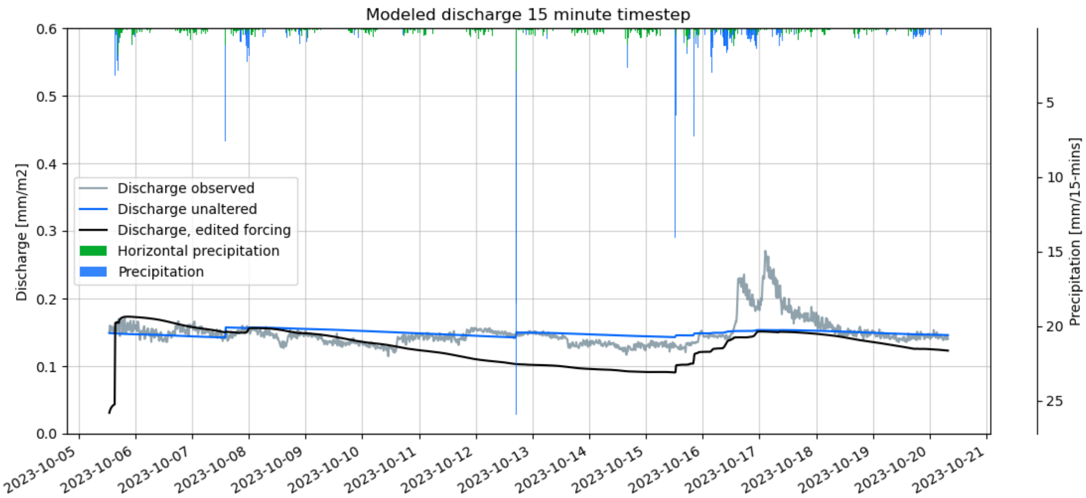


Figure 4.11: Output of the FLEX-Topo model using a 15-minute timestep and using two different types of forcing data. One which is unaltered, resulting in the discharge plotted in blue. And one in which the fording data was edited, leading to the discharge indicated in black. The observed discharge is indicated in grey.

The runs with a one-hour timestep are illustrated in Figure 4.12. It is evident that the run with edited forcing data accurately simulates the peak discharge. In contrast, the unaltered run exhibits a substantial response to the peak on October 13th, comparable to the response to the one-day rain event on October 16th and 17th.

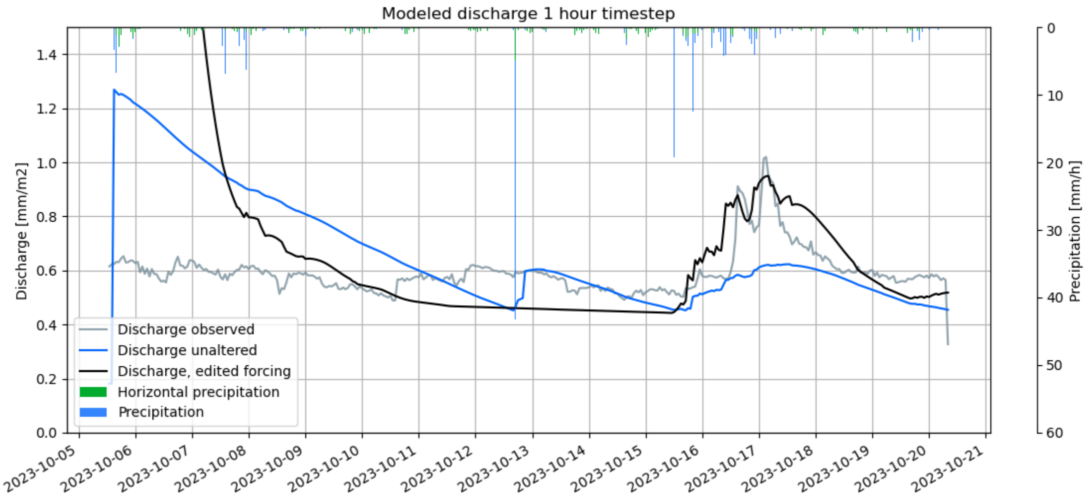


Figure 4.12: Output of the FLEX-Topo model using a 15-minute timestep and using two different types of forcing data. One which is unaltered, resulting in the discharge plotted in blue. And one in which the fording data was edited, leading to the discharge indicated in black. The observed discharge is indicated in grey.

As described in Section 3.5, the Nash-Sutcliffe Efficiency (NSE) coefficient is used to asses the model's goodness of fit. These values, as well as the parameter values of all four runs, can be found in Appendix G. The NSE values indicate that the model's performance is not satisfactory. The positive NSE values for the 15-minute and 1-hour unaltered forcing simulation runs suggest slightly better performance compared to the runs with altered forcing. This suggests that the model's performance is adversely affected by the removal of outliers from the data set. However, visually, both the 15-minute and 1-hour altered forcing runs seem to respond better to rainfall events while maintaining reasonable base flow.

The simulation demonstrates that the runs react differently to the model's beginning states, whether it uses a one-hour time step as opposed to a fifteen-minute one. Even though the initial conditions are equal in all runs, except for the translations between 15-minute timesteps and one-hour timesteps. It is worth noting that the coefficient for evaporation recycling (f_{CL}) is highest in the 1-hour altered run, and this run performs best in capturing peak discharges during rain events. However, the NSE of this run suggests a poor fit, possibly because it exhibits extremely high discharges in the first three days. These discharges were so high that they exceeded the y-axis limit, reaching 20 millimetres on the first day.

4.6.2. Parameters

In this section, the different parameters that are used in the FLEX-Topo model are discussed. First of all, the maximum water storage in the unsaturated bucket, Su_{max}, is expected to be small. But when examining the unsaturated buckets S_u, it appears to fill the first two days. This may be attributed to the model's design, where evaporation is initially drawn from the interception bucket, and extraction from the unsaturated bucket occurs only once the interception bucket is empty, which hardly ever happens during the two-week run. This behaviour could also account for the scattered nature of the β parameter. The tendency of factor D in the class Cloud Forests to be 1 indicates that it prefers to flow into the groundwater (S_s) bucket, instead of directing it to fast flow (Q_f). Next to that, the analysis of the parameters showed that the coefficient for evaporation recycling, f_{CL}, exhibits very small values for all runs. When looking in detail at the runs with a high NSE score, the value of f_{CL} is between 0 and 0.1.

4.7. Stakeholder framework

During this research 18 interviews were conducted with a wide variety of respondents to collect qualitative data, concluding in 12,5 hours of interview data. During these interviews the respondents were questioned about their experiences, challenges as well as strategies for coping with these challenges. In H the overview of all the interviews can be found. During the interviews, mini-stories were collected. These mini-stories contain a challenge as well as a strategy and intervention to cope with this challenge. To further analyse the mini-stories collected from the qualitative interview data. The mini-story was split up into the challenge, strategy and intervention. Table (Table 4.1) gives an overview of the mini-stories, from which respondents it was collected, and which challenge, strategy and intervention it includes. The mini-stories are further categorised into several challenge categories. This method is known as open coding, axial coding and selective coding. This is used in the grounded theory method of analysing qualitative data. The open codes leading to an axial code are eventually lined to an aggregate category. The challenges extracted from the mini-stories act as open codes that are linked to a challenge category. Finally, the categories lead to recommendations for stakeholder engagement strategies for CCFC. This is showed in a constructed figure (Figure 4.13) based on the research of Ninan & Sergeeva, 2022.

Table 4.1: Overview mini-stories, including challenges and strategies.

No	Source	Mini-story	Challenge	Strategy	Intervention
1	*NGO CCFC* Owner	Despite the Environmental Ministry and the Education Ministry recognising the deficiency of environmental knowledge within education programs, they have yet to collaborate. This collaboration is within their respective mandates, but it's now our responsibility to bridge this gap.	While the deficiency in environmental education is acknowledged, the Environmental Ministry and Education Ministry have yet to unite and devise a coordinated plan to address it.	Facilitate collaboration through a joint stakeholder dialogue with both parties, to trigger the government to action.	Stakeholder dialogue, development of education programs and environmental awareness campaigns.
2	*NGO CCFC* Owner	While the Water Distribution Centre acknowledges the critical role of cloud forests in ensuring water security, they have not yet pursued collaboration with environmental institutions to further this understanding. We should help them to start this conversation.	Lack of collaborative initiatives between the water distribution centre and environmental institutions.	Facilitate collaboration through a joint stakeholder dialogue between the two parties.	Stakeholder dialogue.
3	*NGO CCFC* Co-owner	Women in communities often face social marginalisation, including limited access to education. However, they possess significant advocacy capacity, as they play essential roles in caring for their families. Initiating conversations with women and implementing education programs for women and girls can be a powerful step forward.	The social marginalisation and limited access to education that women in communities face.	Empower women through targeted education programs, leveraging their inherent advocacy capacity to drive positive change within their communities.	Community-centered education programs, development of education programs and advocacy .
4	*NGO CCFC* Co-owner	The quality of education is poor and there is a lack of access to education, which is the responsibility of educational institutions, the effectiveness of those institutions is therefore questionable. Education is a crucial factor influencing various aspects of quality of life, including income, health, resource access, and family size. To effectively address these challenges, it is needed to develop a well-rounded education program that addresses the entirety of these issues.	The quality of education and access to education is affected by the effectiveness of educational institutions. Both have a wide-ranging effect on various aspects of people's lives.	Efforts to raise awareness about the importance of education, coupled with the development of a comprehensive education program enhance education quality and access.	Awareness campaigns and development of education programs.

Table 4.1: Continued from previous page

5	*Local university* Professor Hydrology	There is a lack of funding for research, it is less than 0.5% of the GDP. Conducting research in cloud forests is particularly challenging due to its high cost and logistical complexities. Consequently, there is a scarcity of researchers who choose to work in this field, leading to a reliance on international funding and research initiatives.	Conducting research in cloud forest ecosystems is financially challenging due to high costs, logistical complexities and the limited funding provided by the government.	The use of international resource mobilisation (funding, knowledge and researchers).	Collaborating with other entities with more influence.
6	*Local university* Professor Hydrology	Government officials should be well-informed by, engaging experts who understand local realities. Except there is a lack of expertise at top levels and also a lack of willingness to consult external experts. Make alliances with other relevant stakeholders to work together and share knowledge.	Lack of expertise at top levels and unwillingness to seek external input in decision-making processes at higher levels.	Engaging experts through making alliances with relevant stakeholders to work together and share knowledge.	Development of networks and mechanisms to facilitate knowledge exchange, data sharing and collaboration among relevant stakeholders.
7	*Local university* Professor Hydrology	Access to reliable and up-to-date government data is limited, hindering research efforts. However, there is a culture of research, data collection, and knowledge sharing among universities, researchers, and NGOs, facilitating collaboration and information exchange among these entities and researchers.	Lack of up-to-date data sharing from governmental authorities, hindering research efforts.	Effective data sharing among lower-level stakeholders	Development of networks and mechanisms to facilitate knowledge exchange, data sharing, and collaboration among relevant stakeholders.
8	*Cloud forest nature reserve* Owner and Conservation specialist	To have influence at the government level, data plays a crucial role as they provide strong arguments and evidence. We lack the expertise and capacity to conduct research. Therefore, we create space for research and data collection that can be used to convince government authorities.	Data plays a crucial role as they provide data-driven advocacy. Limited influence at the governmental level without research findings, while self not having the capacity to conduct research.	Provide space for research and use these research findings for data-driven advocacy to influence governmental policies and authorities	Creating space for research, data-driven advocacy, and development of networks and mechanisms to facilitate knowledge exchange, data sharing, and collaboration among relevant stakeholders.
9	*Cloud forest nature reserve* Owner and Conservation specialist	The population we work with primarily focuses on their cornfields and often sees the forest as an obstacle to their income. However, part of our approach involves fostering an appreciation for the forest. We help them understand their role as members of the ecosystem and encourage diversifying income streams.	The local population primarily views the forest as an obstacle to their income and is concerned with their cornfields, not seeing the importance of the services the forest provides.	Fostering an appreciation for the forest among the local population. This is achieved by helping them understand their role as members of the ecosystem and encouraging them to diversify their income streams.	Community engagement through building appreciation, environmental awareness campaigns, and community-centered education programs for skill development.

10	*Nature reserve* Owner and Conservation specialist	Nature reserves face vandalism from intruders seeking to profit from the illegal sale of trees, endemic species, and experimental setups. To counteract this, collaboration is sought with local communities, establishing dedicated protection groups.	Vandalism in nature reserves for financial gain, driven by immediate gain and a lack of environmental appreciation.	Community protection against vandalism and illegal deforestation	Community engagement through the employment of locals and communities.
11	*Nature reserve* Owner and Conservation specialist	It's essential to demonstrate the tangible benefits of conservation. We believe that people are more likely to engage in conservation efforts when they can see its profitability, providing opportunities for income and job creation. By involving community members as guides and advocates, they become responsible for their own community's welfare.	The lack of incentive and understanding among local communities regarding the tangible benefits of conservation, only engaging in efforts when they see it as profitable.	Fostering opportunities for income generation and advocacy within communities by employing community members.	Community engagement through the employment of locals and communities and advocacy.
12	*NGO Fundaeco* Conservation science strategies advisor	The incentives are designed to promote reforestation in rural areas, with a specific focus on benefiting local residents who own smaller land parcels. However, they are challenging for the average local resident to access. Our goal is to simplify the enrolment process, provide assistance, and support them in effectively utilising these incentives for their benefit.	Incentives provided by the government are difficult to access for local residents, therefore marked by weak effectiveness and a failure to achieve the intended goals.	Assist local residents through the enrolment process of incentives	Community-centred education programs for skill development through workshops.
13	*NGO Fundaeco* Conservation science strategies advisor	Due to the inefficiency in enforcing governmental policies and a lack of government responsibility, the solution lies in addressing challenges from the grassroots level. This necessitates the development of strong relationships with communities and their leaders and active collaboration with them.	Presence of governmental deficiencies in addressing challenges, such as the inefficiency in enforcing policies and the lack of government responsibility.	Addressing challenges with grassroots-level solutions through building relationships and collaborating with communities and their leaders	Community engagement through actively building relationships with communities and community-based solutions.
14	Student Local Environmental Management	Deforestation poses the most significant threat to cloud forests. The potential for management or complete reversal of this threat hinges on the political landscape. Unfortunately, in Guatemala, a deficiency of political will persists. Therefore, there is a need for awareness campaigns to address this environmental challenge.	There is a need for political will to solve the problem of deforestation, but this will be lacking.	Conduct awareness campaigns aimed at urging the government to acknowledge the threat of deforestation and the need for action	Awareness campaigns.

15	Student Local Environmental Management	Language diversity is an educational challenge in Guatemala, where 24 different languages are spoken. Addressing the language barrier should be done through providing education and resources in multiple languages, ensuring that language diversity is recognized and accommodated in the learning environment.	Language diversity and the associated language barrier in the education system.	Create a more inclusive and effective educational environment accommodating the needs of the local communities	Development of education programs and community-centered education programs.
16	Researcher: specialised in conservation and community engagement	Each community has its unique characteristics, their own languages, histories, and topographies. There is no universal solution that fits all circumstances. It requires tailored approaches for each community, emphasising the need for community-based solutions. It is crucial to employ influential and recognisable icons, symbols, and terminology that reflect the community's identity and resonate with members.	Due to unique community characteristics like languages, histories, and topographies. There is no universal solution that fits all circumstances.	Solve challenges with community-based solutions tailored to the characteristics of the community. Important to employ influential and recognisable icons, symbols, and terminology that reflect the community's identity and resonate with members.	Community-based solutions and employing recognisable icons, symbols, and terminology.
17	Researcher: specialised in conservation and community engagement	Limited education complicates explaining processes like the hydrological cycle and its connection to the cloud forest. Start the conversation with the children. Let them be the advocates of environmental challenges, to friends and family. Involving their parents through educational and reforestation programs.	Lack of education hinders the understanding of essential ecological processes.	Raise awareness, particularly among children and let them be advocates	Environmental children programs and advocacy.
18	Researcher: specialised in conservation and community engagement	Conservation efforts depend largely on privately owned capital. Additionally, making tourism a sustainable income source can be complex, requiring significant upfront investment. This is particularly challenging when working with economically disadvantaged communities. Training and capacity building are essential to empower these communities.	Conservation efforts depend largely on privately owned capital. Economically disadvantaged communities may face financial challenges when trying to leverage tourism as a conservation strategy.	Empower the communities through training and capacity building	Community-centered education program for skill development.

19	*Non-local university* Professor Forest eco-physiology and canopy scientist working area cloud forests	In general, there is a lack of research done in the cloud forest ecosystem. There is only a small community of researchers. Therefore we created a research coordination network (RCN), making it easier to collect funds and pull together these researchers all over the world.	Lack of research in cloud forest ecosystems, with only a small community of researchers.	Creating an RCN to collaborate and collect funds more easily	Development of networks and mechanisms to facilitate knowledge exchange, data sharing, and collaboration among relevant stakeholders.
20	*Non-local university* Professor Forest eco-physiology and canopy scientist working area cloud forests	The cloud forest research community comprises a small number of experts, which led to a big influx of international researchers. One concern with international researchers is the risk of fostering a sense of superiority. This can be detrimental to effective collaboration, understanding, and knowledge sharing. To mitigate this risk, include and collaborate with local experts and communities.	Because of the small number of cloud forest experts, there is a significant presence of international researchers, leading to the potential development of a sense of superiority among international researchers, which is detrimental to effective collaboration and knowledge sharing.	Collaborate together with the local experts and communities	Development of networks and mechanisms to facilitate knowledge exchange, data sharing, and collaboration among relevant stakeholders.
21	Researcher: specialized Mayan Q'eqchi' communities and agriculture	There is migration of small-scale farms higher up the mountain slopes, leading to more deforestation. This shift is driven by the decline in soil quality due to increased surface runoff, decreasing agricultural productivity. It is not recognized that this is related to their own agricultural practices, like deforestation.	Farmers do not recognize the connection between their agricultural practices and their challenges, as well as the environmental consequences of these practices.	Develop environmental education for better environmental awareness of farmers and promote better agricultural practices.	Environmental awareness campaign and community-centered education program for environmental education and skill development.
22	Researcher: specialised Mayan Q'eqchi' communities and agriculture	Some community members have a lack of opportunities for further education or alternative career paths. Consequently, they often follow the traditions of their fathers, becoming farmers like the generations before them. This trend is a reflection of the community's limited opportunities available. Addressing this community-specific challenge should be done by providing tools and resources to enhance available opportunities.	The lack of options available to community members contributes to a cycle of limited career choices spanning multiple generations.	Improving educational and economic opportunities for young people in these communities through initiatives that provide a broader range of options for alternative career paths	Community-centred education programs for skill development and community-centered education programs.

23	Local farmers of larger parcel	Governmental campaigns for the incentive programs are currently lacking, resulting in many individuals in these areas remaining uninformed about the existence of these programs. To address this issue, others need to proactively organise awareness campaigns.	Governmental community outreach for the incentives is ineffective in reaching the intended recipients, they are unaware of the existence of these incentives.	Organising effective awareness campaigns that reach the communities and the intended recipients	Awareness campaigns through posters, radio programs, and social media.
24	Local resident Q'eqchi' mountain village	The village's spring dried up. A consequence of the significantly reduced rainfall that occurred during that period. This link was not initially recognised. Because of this, they need to walk further to another spring to collect water.	Limited understanding among community members of the hydrological cycle and the fundamental concept that spring water primarily originates from precipitation.	Provide environmental education by using environmental campaigns that reach remote communities	Environmental awareness campaigns through radio programs and social media and community-centered education programs for environmental education.
25	*CONAP* Communication Manager	Institutions work on different topics, meaning that there is not yet a collaboration on topics and programs. Although there is a need and overlap in the realms of water, education, and the environment. Until now, other organizations have filled this gap.	Although CONAP recognizes the need to work together with other institutions in the realms of water, education, and the environment, this collaboration is not yet established.	Institutions collaborating together to create more influential programs	Making alliances and collaborating with other actors related to the topic.
26	*CONAP* Communication Manager	For communities, economic viability is essential; conservation may not yield immediate profits and requires a long-term perspective. Many individuals may lack the business acumen necessary to think about initiating and growing a business, as they might not be accustomed to saving and reinvesting properly. Nonprofits can help build this skill and help with income diversification strategies.	Community members lack the business acumen and long-term perspective needed to engage in conservation efforts, especially when immediate profits are not guaranteed.	Non-profit organisations providing programs to enhance business skills and income diversification strategies.	Community-centered education program: for skill development.
27	*INAB* Project manager	Cloud forests are often viewed as obstacles rather than profitable assets, which makes conservation less appealing. To bridge this gap, it's crucial to find common ground. Water security serves as a vital focal point and a compelling argument to initiate conversations about the importance of cloud forest conservation.	Cloud forests are seen as obstacles rather than profitable by locals, making conservation less appealing. This is reinforced by a limited understanding of the importance of them for water security.	Leverage awareness campaigns, using water security as a persuasive argument.	Environmental awareness campaign, community engagement through building appreciation.

28	*INAB* Project manager	INAB does not actively seek engagement with communities but provides support and assistance to others who take the lead in organising initiatives for communities.	INAB is not proactively engaging with communities; they depend on external parties to initiate community-oriented initiatives.	INAB delegates responsibility to other organisations for community initiatives.	Making alliances and collaborating with other actors related to the topic.
29	*World Bank* Project director	International NGOs often have practices and actions that do not effectively address root causes, and they tend to apply a generalised approach by repeating identical projects without considering the specific contexts where they operate.	International NGOs use a generalised approach for their interventions, not considering the specific context of the area or community they operate in.	Fit-for-purpose interventions to the needs and concerns of the area or community.	Community-based solutions.
30	*World Bank* Project director	There is a concern that financial resources allocated for environmental protection are not being managed in an open, clear, or accountable manner. This lack of transparency can lead to problems such as mismanagement of funds, corruption, or inefficiency in achieving environmental goals. Therefore, monitoring programs have started.	Lack of transparency in financial resources allocated for environmental protection can lead to mismanagement of funds, corruption, or inefficiency in achieving environmental goals.	Development of monitoring programs.	Monitoring programs.
31	*NGO Water for the People* Project director	The government's strategy involves delegating tasks to other entities rather than taking direct responsibility. This delegation of responsibility to NGOs shouldn't be the primary method of addressing these gaps, but in practice, NGOs often end up filling these voids.	The government deliberately depends on other organisations for initiatives and delegates tasks, instead of taking direct responsibility.	NGOs are addressing governmental shortcomings.	Making alliances and collaborating with other actors related to the topic.
32	*NGO Water for the People* Project director	INAB acknowledges the importance of forests for recharge zones and, by extension, water security. However, their programs currently lack a specific focus on these recharge zones, and they have not actively sought collaboration with water institutions.	INAB recognises the importance of forests for water security but has not integrated a specific focus on these recharge zones into their programs. There is also a lack of active collaboration between INAB and water institutions.	Facilitate collaboration through a joint stakeholder dialogue between INAB and the water institution to trigger the government to action.	Stakeholder dialogue.

33	*Water distribution centre Cobán* Owner	Around 100,000 city residents rely on water from the cloud forest catchment area. Surprisingly, 80% are unaware of the water's source, perceiving it solely as what flows from their taps. This lack of awareness about the cloud forest's vital role in providing this resource underscores the need for an awareness campaign.	Residents relying on the water from the cloud forest catchment area are unaware of the water's source, meaning a lack of awareness about cloud forests' important services.	Conducting a resident-wide environmental awareness campaign.	Environmental awareness campaign through radio programs, posters, social media, and presentations.
34	*Water distribution centre Cobán* Owner	Water quality and the consistent flow of water are major concerns, particularly due to a lack of awareness regarding the downstream consequences of actions. People residing upstream often have limited knowledge of how their actions can significantly impact downstream areas.	Lack of awareness among upstream communities regarding the consequences of their action on the water quality and quantity in downstream areas.	Environmental awareness campaign to raise understanding of downstream consequences.	Environmental awareness campaign through radio programs, social media, posters, and presentations.
35	Researcher: biodiversity and Mayan Q'eqchi' communities	Begin conversations with children who are naturally fascinated by biodiversity and animals, fostering their appreciation for the forest. By focusing on the younger generation, we ensure that future generations possess the knowledge and understanding required to continue conserving the cloud forest.	Conservation efforts in the future are uncertain because of insufficient environmental awareness and knowledge.	Initiate conversations with children to raise their awareness and appreciation of the forest and its biodiversity to ensure ongoing conservation in the future.	Environmental children programs, a community-centred education program for environmental education and appreciation.
36	Researcher: biodiversity and Mayan Q'eqchi' communities	The challenge is to foster a sense of responsibility for caring for the environment, finding common ground is needed. This can be achieved by using Catholic teachings and Mayan cosmology, which emphasise the responsibility to care for the ecosystem and provide a shared framework and a strong foundation to promote conservation efforts.	Fostering a sense of responsibility for environmental conservation and finding common ground between conservation work and the values of the community.	Find common ground by using Catholic teachings and Mayan cosmology as a shared framework to emphasise the responsibility of caring for the environment and promoting conservation efforts within the community.	Community-based solutions, community engagement through actively building relationships with communities, community engagement through building appreciation and environmental awareness campaigns.

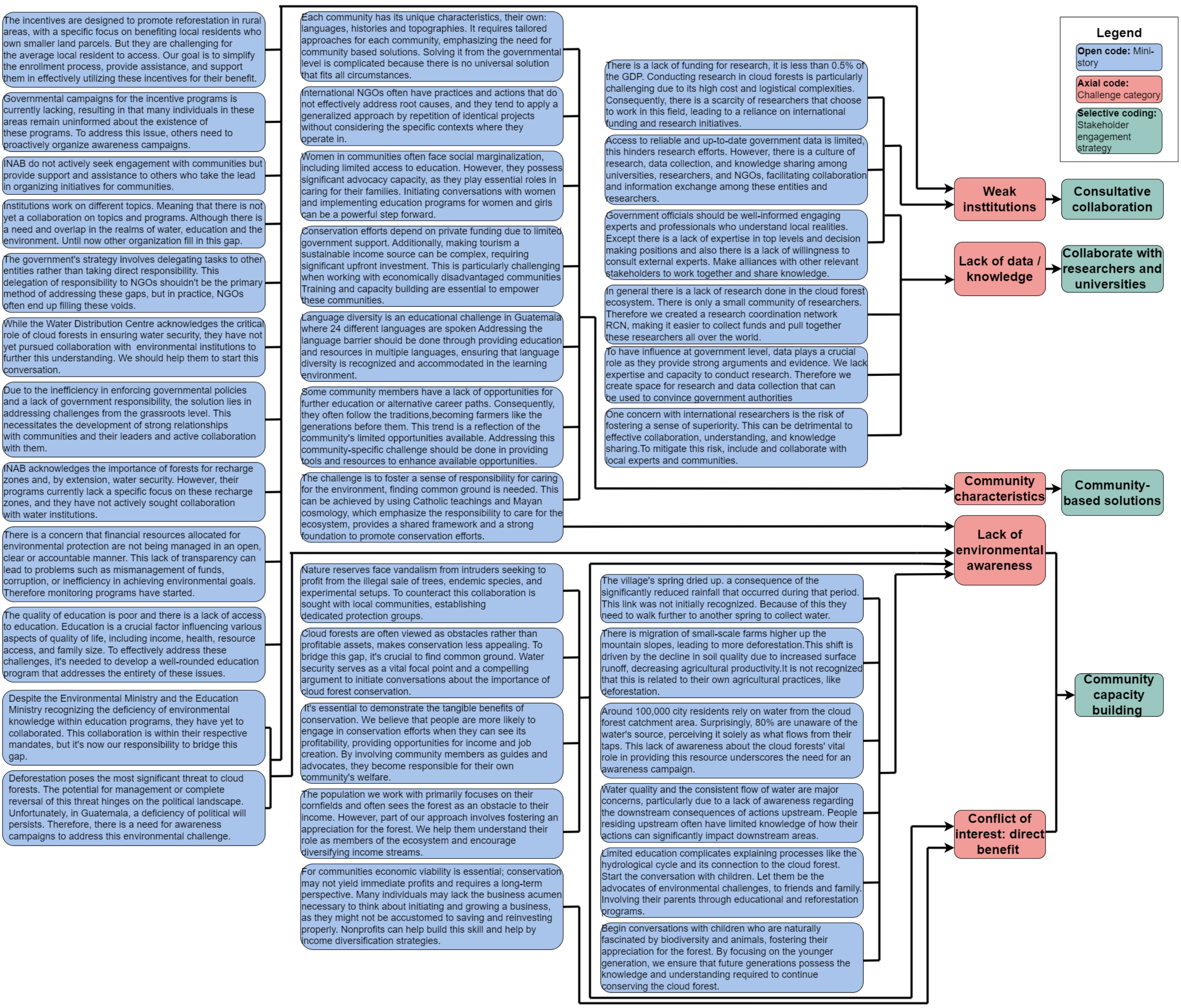


Figure 4.13: Analysis of qualitative data through grounded theory method using open coding, axial coding, and selective coding.

u The following describes the challenge categories and stakeholder engagement strategies mentioned in Figure 4.13

Weak institutions

The challenge of "Weak Institutions" revolves around the inefficiency of government bodies in effectively implementing and enforcing policies, their lack of responsibility, and the ineffectiveness of programs, often failing to achieve their objectives. Additionally, it underscores the absence of collaboration among different institutions working on overlapping realms or issues. This challenge indicates a potential lack of commitment of governmental bodies to address pressing issues adequately. Resulting in limited support for conservation efforts, inadequate policy enforcement, and insufficient engagement with local communities.

Consultative collaboration

Consultative collaboration with the government is a process where external entities actively engage with government bodies to provide advice and recommendations on policy development and governance processes. In this role, they offer input and suggestions on government policies, programs, and projects. Entities engaged in consultative collaboration may also play a crucial role in bringing together the right stakeholders, like multiple governmental institutions, for constructive dialogues. It is instrumental in capacity building within governmental institutions, ultimately contributing to more informed decision-making, improved policies, and better governance. Enhancing the quality and effectiveness of government actions [83].

Lack of data/knowledge

The category challenge "lack of data/knowledge", underscores issues stemming from the insufficiency or absence of essential knowledge, data, or expertise. This categorisation, with a specific emphasis on cloud forests in the context of Guatemala, addresses both a scarcity of data and a shortage of knowledge in the research field, both of which present obstacles to conducting meaningful research. This research is necessary to understand, address or make informed decisions about the unique issues, challenges and opportunities associated with cloud forests. The categorisation of "lack of data/knowledge" is intended to focus on challenges related to higher-level research and knowledge, distinct from issues of local awareness and knowledge.

Collaborate with universities and researchers

Addressing the "lack of data/knowledge" challenges requires enhanced data collection and knowledge sharing. Which can be achieved through collaboration with universities and researchers. Enhanced data collection and knowledge sharing from these collaborations hold a significant influence on policy development, providing evidence-based support.

Community characteristics

The "community characteristics" challenge category addresses issues arising from the distinct features, values, traditions, and attributes of a specific community. These characteristics can encompass a wide range of elements including socioeconomic disparities, cultural practices, beliefs, traditions, histories, and language. These unique characteristics can pose challenges when addressing a community's specific issues and also impact the success of implementing other programs and initiatives.

Community-based solutions

Community-based solutions are tailored to address the specific challenges and needs of each community, adapting to the unique characteristics of each one. Therefore, community-based solutions are well-suited for addressing challenges linked to the challenge category "community characteristics" because they acknowledge and adapt to the distinctive traits of each community. These characteristics play a guiding role in community engagement efforts and solution development. By recognising and comprehending community characteristics, the development of more effective approaches to address the community's challenges as well as successfully integrating other types of initiatives seamlessly. These solutions can be crafted by external stakeholders with community input, although the level of community control may vary [8].

Lack of environmental awareness

The challenge category "Lack of Environmental Awareness" refers to situations where individuals, communities, or institutions lack a fundamental understanding of environmental issues, their significance, and the consequences of human actions, such as deforestation. This deficiency in environmental awareness poses obstacles to the community's capacity to respond to changing conditions. Additionally, a lack of awareness regarding the crucial role of cloud forests in ensuring clean water further complicates endeavours to address water quality and the consistent flow of water.

Conflict of interest: direct benefit

The challenge category "Conflict of Interest: Direct Benefit" involves situations where communities prioritise immediate, short-term financial gains over the long-term benefits of conservation efforts, posing a significant challenge to the conservation of cloud forests. In these scenarios, communities may be motivated by immediate financial gains, such as through activities like logging, land clearance, or selling valuable forest resources. The root of this challenge lies in the community's potential lack of understanding or appreciation for the long-term environmental and ecological advantages of conservation.

Instead, their primary focus centres on immediate financial gains. This focus on short-term economic benefits can lead to actions that harm the environment, including deforestation, unsustainable resource extraction, and even vandalism of protected areas. Moreover, communities pursuing direct financial gain may find themselves in a conflict of interest with conservation efforts.

Community capacity building

Community capacity building is the process of strengthening a community's skills, knowledge, resources, and capabilities of a community. The goal of community capacity building is to empower the community to effectively address its own challenges and make informed decisions, and pursue sustainable development. It involves investing in community members by providing education, training, and tools. This approach fosters ownership and responsibility among community members, making solutions more sustainable. The focus is on ensuring that the capacity developed within the community is sustainable over time. This involves planning for continuity and ongoing development. It encourages knowledge sharing and collaboration within the community and with external partners, to access additional resources. By enhancing a community's skill, knowledge and abilities, it increases resilience to cope and recover from challenges [43, 86].

5
Discussion

The following chapter is dedicated to discussing and interpreting the research findings, presented in Chapter 4. The research aims to find an answer to the research question: *"To what extent does the presence of a cloud forest canopy impact the Mestelá River catchment and how will this affect the various involved stakeholders?"*. This discussion chapter will thoroughly examine the outcomes of this research, carefully considering any limitations. To maintain a structured approach, this chapter will adopt the structure of Chapter 3: Methodology, and systematically analyse the findings on a section-by-section basis.

5.1. Long-term Measurement Site

In this Section, the general performance of the measurement site is discussed. Next to that, the challenges of the construction and maintenance of the site are further explained. One of the important aspects of the construction of the site was to find a suitable location. The drivers for the decision were based on security, proximity, accessibility, internet connection, cloud cover presence and height within the catchment. After careful consideration and cooperation with CCFC, the definitive location was decided upon, as summarised in Figure 3.1.

The advantage of the decided location of the measurement site is its proximity, which resulted in a large logistical advantage. However, the altitude of the site is quite average for the catchment, which can be a disadvantage for cloud interception. The altitude of the measurement site is about 1655 m, which is quite average for the Mestelá catchment with an altitude ranging from 1400 to 2600 meters. The formation of clouds is highly dependent on relative humidity and temperature, these parameters are much more favourable at higher altitudes. Therefore, to measure more clouds and have more data available about cloud interception it would be better to have an experimental area at a higher altitude. However, in this research, it was not possible to achieve this due to the logistical challenges.

Next to that, some of the parameters that are used to describe hydrological processes were not measured at the site, due to the presence of a local weather station (ICOBN4) at a distance of 500 meters. The hydrological processes that were monitored at the measurement station are fog interception, throughfall and stemflow. Other processes such as vertical precipitation, evaporation and pressure were measured at the local weather station. The combination of the data retrieved from two different locations results in difficulties when looking at the timing between events. Moreover, parameters such as temperature and relative humidity can differ a lot in the climate of the Mestelá River catchment, due to the high variability in vegetation and topography.

Another point of discussion is the durability and lifetime of the long-term measurement site. During the first maintenance period of the station, clogging of both tipping buckets occurred. This proved that regular maintenance is one of the most important ways to ensure that the station keeps working. Next to that, the possibility of vandalism is a great risk to the durability of the measurement station.

5.2. Canopy Monitoring

5.2.1. Site Location

As detailed in Section 3.2.2, the decision to construct the long-term canopy site close to CCFC proved wise. However, post-construction, it became evident that maintenance requirements and logistical challenges had been underestimated. Additionally, the measurement site's vulnerability to vandalism remained due to the unavailability of extension cables for the sensors, which is further explained in Chapter 7. Furthermore, a more thorough reconnaissance of the measurement site could be refined, as tree locations were estimated instead of being surveyed, hindering a clear site overview and understanding of the topography for future researchers.

5.2.2. Canopy Influx

During the research, various meteorological events were monitored through the use of the local weather station (ICOBN4), throughfall measurements, and fog traps. In this Section, the results of Section 4.5 are analysed, which involve the measured vertical and horizontal precipitation.

Vertical precipitation

Vertical precipitation is measured at the weather station (ICOBN4), located 500 meters from the measurements site. The area's dynamic topography, characterised by steep mountainsides between the weather station and the measurement site, may introduce variability in rain event behaviour. This variation can be noticed as a time lag for the vertical precipitation at the weather station to reach the long-term measurement station. To mitigate this time lag and enhance the precision of the throughfall measurements, a rain gauge could be installed at the experimental area.

Next to that, a noticeable enhancement to the hydrological FLEX-Topo model would be the addition of an extra weather station within the Mestelá River catchment. In Figure 4.6 the vertical precipitation is plotted together with the Mestelá River discharge. In the upper graph, the response of a heavy and long rain event on the Mestelá River discharge can be seen, with a noticeable time lag of 28 hours between the onset of rain and the initial peak in discharge. However, the rain event occurring on the 12th of October does not have a similar response to the discharge. In this event, the vertical precipitation was short and intense but did not lead to an increase in river discharge. This discrepancy can be explained when looking at the data of another weather station on the same day. The ITAMAH1 weather station is located just outside and on the other end of the catchment. On this day little to no rain was measured. This suggests that the intense rain measured by ICOBN4 was likely a highly localised event, impacting only a small fraction of the catchment and not enough to be noticed in the discharge. This variation in weather patterns can once again be explained due to the topography of the catchment. To resolve this issue, multiple weather stations could be placed in the catchment or the hydrological model could be expanded to a distributed model. This model creates a grid structure of the catchment and interpolates satellite weather data to form a more accurate representation of reality.

Horizontal precipitation

The amount of horizontal precipitation measured at the long-term measurement station was rather limited. During the period of 10 to 14 October, the fog traps were clogged with small debris, resulting in minimal fog interception. Other contributing factors may include the design and positioning of the fog traps. To extract moisture from the air effectively, a significant surface is required. In nature, the leaves of mosses are evolved so that they have enough surface for the moisture to accumulate. To mimic this process, the fog traps are fitted with fishing wire to capture the water from the air. To enhance this process, the addition of an extra set of fishing wire to increase the effective surface could be beneficial.

Due to these limitations and the duration of the project, it was not possible to draw a conclusion related to Figure 4.7, in which fog interception typically occurs after a rain event. An explanation of this phenomenon can only be done when more data is available. This data should be expanded in time (measuring for longer periods) and in space (installing more fog traps).

Next to that, the limited quantity of measured horizontal precipitation is influenced by the climate of the experimental area. The parameters for fog formation are typically preferable at higher altitudes, but also the seasonality could influence this. To address these problems additional fog traps could be installed at higher altitudes, which could perform measurements throughout the whole year. This could lead to more comprehensive data on horizontal precipitation and give a better understanding of the seasonal varieties.

Another noteworthy point is the need for further normalisation of the measured intercepted fog compared to the actual horizontal precipitation input in the system. Currently, the fog interception is normalised based solely on the surface area of the fog traps. However, a more comprehensive approach would involve defining the amount of intercepted fog in terms of millimetres per square meter of ground area. This would involve an extensive survey of all the epiphytes in the catchment, to determine the total effective surface per square meter of ground area. While this study does not undertake that analysis, it has the potential to provide a more meaningful relationship between the amount of intercepted fog and horizontal precipitation in mm/m^2.

5.2.3. Interception and Storage

In this Section, the physical interpretation of the interception and storage processes are discussed. At the beginning of the project, two experiments concerning the storage capacity and evaporation of non-vascular epiphytes were intended. However, due to road blockades in Guatemala that delayed the tree climbing instructor's arrival, the necessary samples were collected later than planned. In addition, limited measuring equipment capacity led to the decision to execute only the evaporation experiment, foregoing the storage experiment.

The results of the evaporation experiment showed that over 4 days, the epiphyte's total weight decreased by 33%, illustrating the slow release of water from epiphytes in the cloud forest climate. This demonstrates their role as a buffer, collecting both vertical and horizontal precipitation and gradually releasing it through dripping and evaporation into the ecosystem. This illustrates why there is no visible increase in the river discharge due to fog events. As the adsorbed water is only released very slowly. However, the evaporation experiment also has its limitations. Time constraints may have prevented the evaporation rate from stabilising, suggesting ongoing water evaporation from the epiphyte. Additionally, because no measurements were conducted at night, and considering the high relative humidity during those hours, it's possible that the epiphyte resumed intercepting water.

5.2.4. Canopy Outflux

Throughfall

The throughfall measurements were performed by installing 4 collecting tubes at the measurement site. The total collection area was 1 m^2. However, these measurements are maintenance-dependent as the tipping bucket can fill up with debris and clog the system. As mentioned before, a noticeable time lag can be seen between the vertical precipitation and the throughfall. One explanation for this could be the difference between the two measurement points and the topography of the area, but it could also be explained by the interception capacity of the canopy. As it starts raining, the canopy of the trees delays the time it takes for the water to reach the ground. During this path, the water can also be absorbed by different epiphytes and mosses. Once they have reached their water capacity, they start to slowly release the water. This, together with the canopy interception, results in a significant delay between the start of the rain and when it is measured in the tipping bucket. To better understand this delay and reduce measurement errors, a weather station should be placed close to the throughfall measurements.

Stemflow

In this project, stemflow is measured by wrapping a flexible tube around the large oak tree's stem at the site. The installation posed challenges due to the tree's irregular shape. Additionally, the narrow tube is prone to clogging as debris can easily enter, potentially resulting in an incomplete collection of the stemflow. Next to that, there were some difficulties concerning the size of the collection bottle. In the beginning, it was decided to use a 2.3 L bottle, but this ended up filling up in 5 days as can be seen in Figure 5.1. Then, it was decided to install an 18 L bottle for the collection. However, this has proven to be too big - the water level in the bottle started to fluctuate as water began to evaporate.

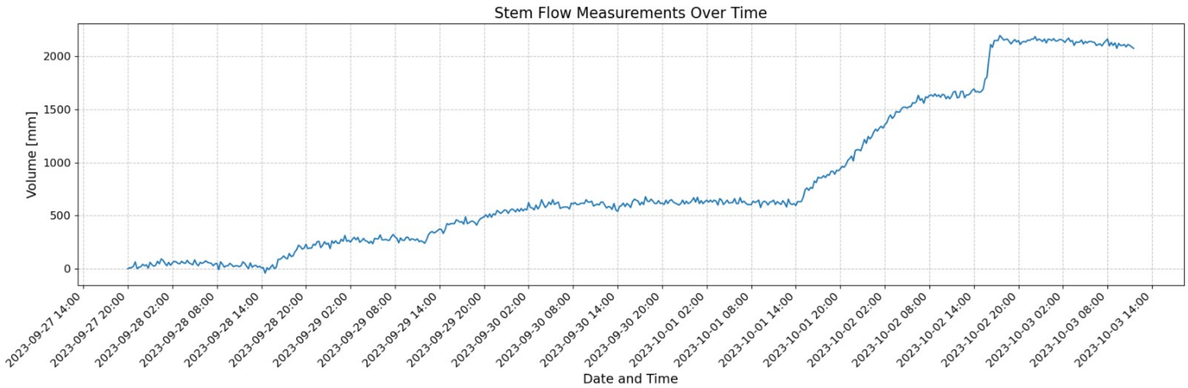


Figure 5.1: The water level in the bottle stabilises around the maximum volume of 2200 millimetres.

Potential evaporation
The potential evaporation is calculated based on the parameters of temperature, solar radiation and relative humidity. These parameters were all measured at the local weather station (ICOBN4). To improve the accuracy of the potential evaporation, these parameters should be measured at the location of the canopy site.

Soil moisture content
The soil moisture sensor installed at the long-term measurement site does not yet enhance the canopy monitoring system or the hydrological model. This is because the FLEX-Topo model is conceptual, meaning its parameters contain no physical meaning, making it impossible to refine them based on physical measurements such as the soil moisture content. Additionally, the sensor's single-point installation within the entire catchment provides limited insights into hydrological processes over the whole catchment.

5.3. Mestelá River Discharge

The discharge model for the Mestelá River demonstrates promising performance, further enhancing the overall effectiveness of the hydrological FLEX-Topo model. The calculated diver velocity and average flow velocity of the river correspond closely with the initial expected river flow. This would suggest that the discharge model is accurate and represents the characteristics of the Mestelá River hydrological behaviour.

The methodology for determining the river's flow velocity, as described in Section 3.4, involves fitting u^* for each data point from the stilling well to match the known diver velocity at a specific point in the river. The obtained logarithmic velocity profile gives an accurate representation of the actual flow velocity for that point in the river. To calculate the average velocity for the whole river, the model estimates the flow velocities of other water depths based on the curve specific to the diver's location. This estimation would be relatively close to the actual value, but to achieve even greater precision, it would be ideal to install multiple divers across the rivers' cross-section. This allows the model to better estimate the vertical average flow velocity for different water heights and therefore also a more accurate discharge. Regrettably, this could not be achieved due to the limitation in the availability of divers borrowed from the Delft University of Technology.

With the obtained discharge from the model a rating curve for the Mestelá River is made, see Figure 4.4. The power law function used for this rating curve demonstrates a strong fit when compared to rating curves from rivers with similar cross-sections. While this is a positive indication, additional measures should be considered to assess the model's accuracy. Such as evaluating the variance associated with each data point and calculating the confidence interval for the rating curve.

In Figure 4.5, the variation of each data point is shown. Here, a variation for the water level is 2 cm, as provided by the manufacturer, and the variation of the discharge is estimated to be 10% of the output.

With this variation, a 95% confidence interval could be constructed around the rating curve. It is important to acknowledge that the accuracy of the rating curve can be improved by increasing the number of data points, expanding the range of water level measurements, or reducing the variation of data points.

Another aspect related to the accuracy of the model is the changing bathymetry of the river. As the water level can fluctuate heavily after periods of rain, the flow velocity changes with it. This causes some points of the sandy river bed to erode with high water velocity and other points to accumulate with lower flow velocities. This has an impact on the calculated effective surface that is used to determine the discharge.

The discharge model contributes significantly to the long-term vision of the research. The recently installed river beacon provides the opportunity to monitor the water levels without the need for divers. The systematic monitoring of this beacon allows that, with the rating curve, an indication of the discharge can be made.

5.4. FLEX-Topo Model

In this section, the landscape classification, adaptations and model performance of the FLEX-Topo model are discussed in detail.

5.4.1. Landscape Classification

The classification of the Mestelá River catchment is based on the Leaf Area Index (LAI) and the height above the nearest drainage (HAND). The HAND is currently set at 8 meters but could potentially be adjusted to 5 meters, which is the initial value upon which FLEX-Topo is based. The LAI was used as a classification constraint because it is directly related to the amount of leaves per square meter. The value of LAI was chosen to best match the spectral analysis. However, it is worth considering using this spectral analysis as the basis for the model's classifications. Currently, a significant portion of the pine plantation in the west of the catchment, of which it is known that there are no epiphytes and mosses on the trees, is being classified as cloud forest.

5.4.2. Adaptations

First, the adaptation of the moisture buffer release is discussed. The moisture buffer release now takes place when the volume in the interception bucket is larger than a threshold parameter value (I_{min}) which is calibrated in the model. It is important to note that this release process follows a linear pattern. This linear pattern results in large moisture leaking, even when the volume in the interception bucket is just slightly above the minimum. An addition to the method would be to calculate the volume leaking using a logarithmic approach. This approach would result in more significant water leakage when the volume in the interception bucket is high. Alternatively, increasing the minimum calibration value, denoted as I_{min}, could be considered to reduce water leakage. This adjustment is necessary because the current volume leaving the interception bucket exceeds expectations.

Next to that, the process of mist condensation, which enters the class cloud forest as horizontal precipitation, is now calculated as the moisture in the air that condenses when the temperature drops and the relative humidity exceeds 90%. The reason mist condensation was applied, rather than the influx of horizontal precipitation measured at the site was that the current collected data was minimal. To still introduce horizontal precipitation in the model, moisture condensation due to saturation in the air in combination with temperature drops was added. With this process, the influx of horizontal precipitation is still added as a result of measurements, rather than a percentage of moisture recycling. One thing to note is that the measurements used for this calculation are solely from the measuring station at CCFC. Given that the calculation is sensitive to pressure, this single-source data, which is not situated in a forest, can be very influential. Better would be to measure the relative humidity and temperature at the site, after which it can be normalised for the entire catchment using a method yet to be determined. However, with this approach, the amount of horizontal precipitation that now enters the system is of the same volume as the vertical precipitation, which might be an overestimate. To decrease this volume, two solutions can be used: (1) increase the relative humidity threshold from 90% to 98% or (2) decrease the assumed average forest height, which is now set at 8 meters.

5.4.3. Model Performance and Value

The choice of adopting a FLEX-Topo model is rooted in its topography-based nature, which aligns well with the characteristics of cloud forests. Opting to choose a FLEX-Topo model over a simpler HBV model, is that the model is more extensive and it will be further optimized in future research. The FLEX-Topo model has more potential for adaptations and future improvements, such as land-use change, and classification adaptations. Next to that, it is worth noting that horizontal precipitation is only relevant in the catchment area containing cloud forests, a distinction that cannot be made in an HBV model. The current format of the FLEX-Topo model contains 19 parameters, some of which are shared among classes. This sharing is justified in the sense that agricultural and cloud forest plots are similar in topography, but different in above-ground dynamics. Moreover, combining them reduces the number of parameters to simulate.

It is essential to acknowledge that the model's time range is too short for an in-depth analysis, in which hydrological signatures are used. This short time range makes overfitting a concern. Additionally, the absence of spin-up time to initialise the model states prior to objective function calculations adds to the issue. One potential solution for the absence of spin-up time could be to duplicate the forcing data and the measured discharge and focus on the objective function calculations in the second half of the results. Unfortunately, time constraints hindered the implementation of this solution. Next to that, the parameter plots shown in Appendix G reveal a lack of patterns, indicating equifinality among the model runs, meaning that multiple configurations of parameter sets could lead to a well-fitted model simulation.

5.5. Stakeholder Management

In this Section, the following topics related to stakeholder management are discussed: the stakeholder engagement strategies and the developed stakeholder framework.

5.5.1. Stakeholder engagement strategies

As seen in the results of the stakeholder framework the stakeholder engagement strategies recommended for the NGO CCFC are: consultative collaboration, collaboration with universities and researchers, community-based solutions and community capacity building. The following sections describe these stakeholder engagement strategy recommendations in more depth.

Consultative collaboration

Many challenges identified during interviews related to 'weak institutions' can be effectively addressed through consultative collaboration. The consultative collaboration facilitates advising to enhance operational effectiveness, resulting in the collaborative design of impactful programs. The interventions and strategies in Table 4.1, related to challenges under weak institutions, are well-aligned with the principles of consultative collaboration. The interventions used are the development of education programs and awareness campaigns, fostering stakeholder dialogue, and making alliances and collaborating with other actors related to the topic.

Among the listed strategies and interventions, some stand out and are further explained. These include (1) the development and oversight of governmental programs, (2) fostering community engagement at the grassroots level to tackle problems by establishing relationships and collaborating with communities and their leaders, (3) assisting local residents in navigating incentive enrolment processes and (4) organising impactful awareness campaigns that reach communities effectively. These strategies and interventions were proposed as solutions because the challenges are primarily linked to institutional shortcomings. They are closely aligned with the approach of addressing these institutional shortcomings by bridging the gaps in governmental policies through community-based solutions and monitoring programs. However, it is important to note that solely relying on community-based solutions and monitoring programs may not fully address the underlying causes of the challenges associated with "weak institutions."

Consultative collaboration represents a holistic approach to addressing issues arising from weak institutions, through advisory and collaborative efforts and fostering dialogue among relevant institutions to enhance the design and effectiveness of government policies. Consultative collaboration involves the initiation of specific stakeholder dialogues with the appropriate parties, to initiate collaborative initiatives between them. These dialogues serve as a constructive platform for interaction, enabling the collaborative development of more impactful programs in overlapping domains of institutions, such as environmental and water issues. Also through consultative collaboration deficiencies and inefficiencies of policies can be addressed by collaborating to come up with strategies aimed at mitigating the identified weaknesses. Resulting in more fitting and impactful programs making government actions more effective in solving the identified problems and reaching its intended goals. For example, through collaborative and consulting efforts, improving governmental awareness campaigns and streamlining the enrolment process to ensure that incentives are better aligned with their objectives and effectively reach communities.

Collaboration with universities and researchers
'Lack of data/knowledge' in the context of Guatemala's cloud forests should be addressed through collaboration with universities and researchers. These partnerships are essential as they bring specialised expertise and research skills to the table, enabling in-depth studies and data gathering critical for effective conservation strategies and data-driven advocacy. When organisations or entities lack the expertise and capacity for research, making collaborative efforts with universities and researchers is vital for knowledge and data acquisition. These collaborations, whether local or international, foster the exchange of best practices and resources, enhancing research quality in the relatively small cloud forest expertise community. The research findings from these collaborations hold a significant influence on policy development, providing evidence-based support for environmental policies.

The interventions and strategies found in Table 4.1, which pertain to challenges categorised as "lack of data/knowledge," demonstrate a strong alignment with the strategy of collaborating with researchers and universities. For example, strategies such as facilitating research opportunities for others when in-house research capacity is lacking, building networks and mechanisms for knowledge exchange, promoting data sharing and collaboration among various stakeholders, including fellow researchers and universities, and forming partnerships with influential entities, such as international researchers with funding access. These approaches contribute to addressing the challenges associated with the lack of data and knowledge in the cloud forest research field. Ultimately, this leads to data-driven advocacy for more informed decision-making and conservation efforts. In sum, collaborating with universities and researchers is instrumental in overcoming the "lack of data/knowledge" challenge, ultimately contributing to the sustainable conservation and management of Guatemala's cloud forests.

Community-based solutions
Community-based solutions take into account community characteristics such as socioeconomic disparities, cultural practices, beliefs, traditions, histories, geography and languages. These characteristics play a guiding role in community engagement efforts and solution development. Recognise that what works in one community may not work in another due to differences in characteristics. By recognising and comprehending these characteristics, the development of more effective approaches to tackle the community's challenges while also implementing other types of initiatives seamlessly. The interventions and strategies in Table 4.1, related to challenges under 'community characteristics', are well-aligned with community-based solutions. For example, they involve community-centred education programs and community advocacy. These strategies are customised to fit the needs and unique characteristics of each community, recognising the importance of language, addressing issues like women's marginalisation, overcoming economic disadvantages rooted in traditions, and creating tailored interventions. In essence, community-based solutions are community-focused and adapt to local conditions, promoting both community development and conservation efforts.

Community capacity building
Challenges of 'Conflict of interest: Direct benefit' and 'lack of environmental awareness' go hand in hand together. Without awareness, individuals and communities may lack the motivation to adopt sustainable behaviours and practices, make environmentally responsible choices, or support conservation efforts. By raising awareness about the importance of preserving the cloud forest, its role in water supply, and the consequences of deforestation, it becomes possible to foster a deeper appreciation for the

environment and drive positive changes in behaviours and practices. Environmental awareness helps individuals and communities understand that prioritising short-term financial gains, as seen in activities like logging, they can lead to environmental degradation and the loss of vital ecosystem services. Which may have detrimental long-term consequences for both the environment and the community's well-being.

The interrelated challenges can be effectively addressed by implementing community capacity building strategies that build on environmental consciousness as well as skill development. Community capacity building empowers individuals and communities with the knowledge and skills they need to understand and address environmental issues. Through educational initiatives like skill development and environmental awareness, communities get informed about the interconnection between their actions with environmental changes and the importance of environmental conservation. Community capacity building can help to provide programs for skill development, to consider alternative environmentally friendly economic opportunities, helping them to diversify their incomes and develop sustainable economic alternatives for communities.

Moreover, capacity building can help bridge the gap between short-term financial interests and the long-term benefits of conservation. By fostering a deeper understanding of ecological systems and the interdependence between humans and the environment, both challenges can be mitigated, promoting more sustainable and environmentally responsible behaviour. Capacity-building programs can lead to changes in behaviour, practices and attitudes leading to being better equipped to make informed decisions regarding their economic activities and environmental conservation. They are better equipped to assess the ecological impact of their actions, reducing environmental harm and increasing their awareness of the impact of their actions.

Establishing mechanisms for shared benefits, where communities can derive economic value from conservation efforts, for example, the intervention of employing locals/communities as guides. These environmentally aware individuals can serve as advocates for conservation within their communities. They become advocates for change, spreading awareness to friends, family, and broader networks.

The interventions and strategies in Table 4.1, related to challenges under "lack of environmental awareness" and "conflict of interest: direct benefit", are well-aligned with community capacity building. These interventions and strategies include environmental awareness campaigns and community-centered education programs: for environmental education and skill development, environmental children programs, advocacy and community engagement through employment of locals/communities and appreciation.

5.5.2. Stakeholder management framework

As outlined in the literature review, CCFC operates in a multi-stakeholder and multi-issue environment. To effectively address the challenges specific to CCFC in this setting, there is a need for a comprehensive approach which is designed to address the environment's complexity. The recommended stakeholder engagement strategies for CCFC involve effectively engaging with the diverse stakeholders in the multi-stakeholder environment to address the multiple issues/challenges present in this complex, multi-issue context. The recommended stakeholder engagement strategies for CCFC encompass specific approaches tailored to multiple stakeholders.

- Institutions of the government: Consultative collaboration
- Communities: Community capacity building through community-based solutions
- Researchers and universities: Collaboration

The stakeholder engagement strategies, based on insights from interviews, adopt a two-fold approach, engaging stakeholders at multiple levels. As highlighted in the literature review, interventions can be implemented through both top-down and bottom-up approaches. To initiate top-down strategies at the institutional level and leverage their advantages, CCFC should employ consultative collaboration through data-driven advocacy. Meanwhile, bottom-up approaches can be executed through community capacity building through community-based solutions.

As mentioned in the methodology one step is to come up with interventions. Working collaboratively with CCFC to translate the stakeholder engagement strategies into actionable steps and initiatives. The interventions are based on the strategies and ideas mentioned during the interviews, ensuring that the challenges collected during the interviews are covered, thereby trying to maximise their impact and effectiveness. The interventions are chosen to cover needs in CCFC's operations, fitting the stakeholder engagement strategies that are derived from the analysis. The findings of this part of the research and their importance are acknowledged by CCFC. It is worth noting that these findings serve as not just a discovery, but also an affirmation of their commitment and efforts in addressing the identified issues. This reinforces the significance of CCFC's work in this context. The intervention and related actions that resulted from the stakeholder framework are discussed in the following sections.

Top-down intervention: Consultative collaboration through data-driven advocacy

As mentioned addressing the 'lack of data/knowledge' in the context of Guatemala's cloud forests necessitates a strategic partnership with universities and researchers.CCFC currently lacks the research capacity required, underscoring the importance of collaborating with academic institutions and experts. Our project serves as such a collaboration, focused on enhancing data collection and knowledge acquisition of the role of the cloud forest in the Mestelá River catchment. In this way, the project contributes to expanding the body of research and data available within the relatively small cloud forest expertise community, directly addressing the challenges associated with 'lack of data/knowledge'. Moreover, the strategy proposed incorporates consultative collaboration with the government to solve the challenges of 'weak institutions', a process in which external entities actively engage with government bodies to provide advice and recommendations for policy development and governance processes. In this role, CCFC can offer input and suggestions on government policies, programs, and projects. Entities engaged in consultative collaboration play a crucial role in bringing together the right stakeholders, like multiple governmental institutions, for constructive dialogues. It is instrumental in capacity building within governmental institutions, ultimately contributing to more informed decision-making, improved policies, and better governance. Enhancing the quality and effectiveness of government actions.

To achieve this, the recommendation is the use of data-driven advocacy as the starting point for initiating critical conversations. This involves bringing together the right stakeholders, most importantly the right institutions which are essential for the collaborative development of more influential programs. The lack of data/knowledge is an obstacle to this data-driven advocacy. Our project can be seen as a catalyst for policies and conversations on an institutional level. The research findings resulting from projects building upon our work and model can be used for consultative collaboration through data-driven advocacy, with a focus on water security. For instance, this could involve collaborations between water distribution centres and INAB and CONAP to start the conversation about the development of protection programs for water recharge zones. Using water security as an important focal point. Data-driven advocacy serves as a tool to raise awareness within these institutions and facilitate the development of more influential, evidence-based programs.

This holistic approach integrates consultative collaboration with data-driven advocacy, using the insights generated from our (future) data. In essence, our project not only contributes to filling the existing knowledge gap but also plays a pivotal role in engaging government stakeholders to ensure the development of effective conservation efforts. The approach and recommendation are fitting for initiating top-down interventions because they actively engage government institutions, contribute to policy development, build institutional capacity, and influence stakeholder dialogues. Initiating top-down approaches makes it possible to leverage the advantages listed in Table 2.1.

CCFC actively engages in collaborative efforts with researchers and universities to expand knowledge, data, and awareness regarding the significance of cloud forests. They offer research spaces, as demonstrated in this project, making their valuable contribution to addressing the lack of data and knowledge about cloud forests. CCFC recognises the significance of engaging in and initiating stakeholder dialogues and the need for collaborative action and using data-driven advocacy, through using our project, to strengthen the foundation and enhance the rationale for their initiatives. They have also highlighted the potential for further development in building sustainable partnerships with these stakeholders in the future.

Bottom up interventions: Community capacity building through community-based solutions
As mentioned addressing challenges of 'Conflict of interest: Direct benefit' and 'Lack of environmental awareness' can be both addressed with the use of solutions in the form of community capacity building. Community capacity building is a recognised community-based solution as it directly empowers and engages the community in addressing its challenges and needs by providing essential skills, knowledge, and abilities to individuals and groups within the community, ultimately enhancing the community's capacity. As previously mentioned, the application of community-based solutions to address challenges linked to community characteristics is instrumental. These community-based solutions mentioned then take into account the community characteristics as well as seek to solve the community's unique challenges. This integration allows for the inclusion of these community-specific traits in community capacity-building programs. In doing so, it not only helps to address the unique challenges within the community but also tailors capacity building initiatives to the community's specific characteristics. This can significantly enhance the effectiveness of community capacity building initiatives. Therefore, the solutions that arise from capacity-building efforts are tailored to the community's specific situation, ensuring that they are relevant and effective [86], [8].

When capacity building is designed to be context-specific. It recognises that each community has its unique characteristics, needs and strengths. It is designed to incorporate local customs, traditions, and languages, making the educational efforts more culturally relevant and engaging for the community. It ensures inclusivity and addresses the unique challenges. When integrated into community-based solutions, environmental awareness campaigns can better resonate with the community, making it more likely that they will engage with the information and consider the importance of finding common ground. In those campaigns, it is crucial to employ influential and recognisable icons, symbols and terminology that reflect the community's identity and resonate with members. These solutions incorporate community-specific needs, values, and traditions, streamlining the process of finding common ground between economic interests and ecological goals. As well as balance the needs of the community and the preservation of valuable ecosystems. Integration facilitates a shared understanding and facilitating the successful implementation of initiatives.

Community-based solutions can encourage active participation from community members in implementation processes. This involvement fosters a sense of ownership and commitment to the solutions, which is often lacking in top-down interventions and externally imposed approaches. Therefore these forms of solutions focus on mobilising local resources, both human and material, to address community issues. This includes leveraging local talent, assets, and traditional knowledge. Building community capacity leverages local knowledge and expertise. Communities often have a deep understanding of their specific environmental challenges and cultural context. By tapping into this expertise, solutions can be even more tailored and effective. Engaging local communities and empowering them to participate aligns with a bottom-up intervention, allowing to utilise of the advantages listed in Table 2.1. Leveraging community capacity building through community-based solutions harnesses the benefits of bottom-up approaches, making it a fitting strategy. Environmentally aware individuals can become advocates for conservation within their communities. They can educate others about the ecological value of cloud forests Community capacity building is not just about short-term fixes but aims for long-term positive change. As the community becomes more capable, it creates a sustainable model for addressing ongoing and future challenges. The community becomes better equipped to identify, respond to, and adapt to issues, reducing the need for external interventions.

As mentioned in the interviews, there is a consensus about the importance of beginning with children as they often have a higher receptivity to environmental concepts due to their higher appreciation for biodiversity. Therefore, they have the potential to become passionate advocates. Initiating programs that involve children, thereby motivating their parents and family, can help cultivate a culture of environmental stewardship throughout the entire community. Resulting in a long-term impact, as future generations inherit and continue to build on environmental awareness and practices. Community capacity building through community-based solutions therefore focuses on long-term sustainability and tailoring solutions to each community's unique needs and characteristics. Given that CCFC's mission revolves around holistic, community-centered approaches to conserving cloud forests and addressing critical challenges related to poverty, education, and social development. CCFC is already actively implementing community-based initiatives and is dedicated to enhancing the capacity of mountainous village communities. The discovery that community-based solutions and community capacity building are the most appropriate stakeholder engagement strategy, establishes a strong foundation for future endeavours. It also forms a compelling argument for the effectiveness of their community-based solutions.

Translating interventions into action: Comic strip

One intervention resulting from the stakeholder framework was also put into action; a comic strip was developed. The comic represents a means of translating the knowledge gained throughout our project into accessible information for local children, fostering their environmental awareness. This is done in collaboration with CCFC and a local student from the University of San Carlos. We are transforming this knowledge into an educational comic for children. This initiative is fitting to the bottom-up interventions.

It is chosen to develop a comic specifically designed for children aged 8 to 10. This age group is ideal because they have likely been introduced to fundamental concepts of the hydrological cycle in school. Through this comic, our objective is to cultivate their understanding of the critical role that cloud forests play in maintaining water resources. Our goal is to make this information accessible and engaging for children in the local communities. Next to this, CCFC hosts the “kids & birds” children's program, which serves as a valuable platform for the distribution of the comic. The comic can serve as educational material for the environmental education given during the program. Enabling children to bring the knowledge back home in the form of a comic and share what they have learned with their parents and friends.

Also, the comic tries to empower girls by featuring Chaim, a resilient Q'eqchi' girl as the main character, to try to address the challenges faced by girls and women due to social marginalization. Chaim's name, inspired by Rubel Chaim, reflects the essence of the place and carries the meaning of ”star” in the Q'eqchi' language. This approach promotes inclusivity and aligns seamlessly with CCFC's WALC program, which is dedicated to addressing the issue of social marginalization of women within communities.
The other main character is Chipi Chipi, a tree frog native to the unique ecosystems of Rubel Chaim and the Cloud Forests. Chipi Chipi serves as a symbol of the critical role played by these cloud forests in preserving biodiversity. The name is derived from the Q'eqchi' language, translates to ”drizzling,” reflecting the frog's connection to the water cycle. Through the insights of this character the water cycle and the services of the cloud forests are explained.

This initiative aims to promote environmental awareness and address the conflict of interest between immediate benefits and conservation efforts. Our approach not only fosters environmental awareness but also takes into account the unique characteristics of the local communities. Incorporating community characteristics significantly enhances the likelihood of the initiative's acceptance and success. It empowers community members to become advocates for the importance of the cloud forest ecosystem, utilising water security as a persuasive argument. This intervention effectively falls under the category of community capacity building, addressing the challenges of lack of environmental awareness, conflicts of interest related to immediate gains (conflict of interest: direct benefit), and the unique characteristics of the communities within CCFC's working area.

The development of this approach is based on insights gathered from the strategies discussed during the interviews. It is chosen to make the comic culturally relevant, following the recommendations for community-based solutions that align with the unique characteristics of the communities. This approach involves integrating local customs and traditions into the comic, enhancing its cultural relevance and making it more engaging for the children in the communities. Additionally, the comic can be developed in multiple languages to maximise its accessibility and impact. Furthermore, a comic is highly suitable for distribution to remote towns due to its ease of dissemination. As mentioned during the interviews, integrating environmental awareness campaigns necessitates a strong resonance with the community members, making it more likely that they will engage with the information. Therefore it is crucial to incorporate influential and recognisable icons, symbols and terminology that reflect the community's identity and effectively connect with the children. The imagery used includes the quetzal, a young Q'eqchi' girl, Mount Xucaneb, and a pila. This imagery has been selected to establish a deeper connection with children, making the message more relatable and impactful.

The entire comic strip was crafted in collaboration with a local student. Together, we made the storyline and laid the foundation with initial conceptual drawings. This invaluable contribution played a pivotal role in shaping a storyline making sure it resonates with little Guatemalan children. The collaboration between CCFC helped on the cultural and community relevance of the comic. This collaboration not only ensures that the comic aligns with the requirements of the local communities but also fulfils the needs of CCFC. The chosen intervention is now in the process of being developed. This development phase involves collaborative planning, with a local student and in partnership with CCFC, both actively involved in this effort. The storyline and conceptual drawings are complete, and an external professional is sought to handle the digitalisation. An example of a digitalised page is provided in the appendix.

Since the comic is currently in development, a set of recommendations for monitoring the initiative's success is provided for utilization by CCFC.
Regularly collecting data will help evaluate the comic's effectiveness in achieving its intended goals and influence. This information can guide adjustments and improvements to the intervention to ensure its long-term impact. It is important to measure the effectiveness of the environmental comic in increasing knowledge, awareness, and behavior change related to the hydrological cycle, conservation, and the importance of cloud forests among children in mountain villages, as well as its influence on community engagement and emotional connection to nature. Key components of a monitoring plan include the following:

- Conduct pre- and post-intervention assessments to measure the knowledge gained by children about the hydrological cycle, importance of cloud forests, deforestation, and conservation.
- Administer surveys with children to understand how the comic has influenced children's emotional connection to nature and the environment.
- Administer surveys with teachers to gauge changes in awareness, attitudes, and behaviors related to conservation. Gather feedback from them about the impact of the comic on children's understanding of environmental issues.
- Monitor the establishment of community initiatives or programs related to environmental conservation that may have been inspired by the comic. Track specific actions taken by children and the community, such as planting trees, and assess whether these actions are linked to the comic's influence.

I contains survey monitoring questions tailored for childrens and teachers, designed to be utilized by CCFC. Also, an assessment list for CCFC to evaluate the impact of the comic based on the responses obtained from children and teachers in other surveys is given.

6 Conclusion

This research related to studying the cloud forest in Alta Verapaz, Guatemala was based on the following research question. *"To what extent does the presence of a cloud forest canopy impact the Mestelá River catchment and how will this affect the various involved stakeholders?"*. This preparatory project represented the first step in researching the importance of Cloud Forests in Alta Verapaz, related to water security and the social impact of CCFC.

To address this question, the hydrograph in relation to both horizontal and vertical precipitation was examined, as explained in Section 4.5. This showed that the Mestelá River seems to be sensitive to vertical precipitation. However, the data range is too short to draw any lasting conclusions on the river sensitivity. The relation between the horizontal precipitation and the discharge in the Mestelá River is difficult to distinguish. Consequently, the hydrograph did not yet provide insights into the extent to which the presence of the cloud forest impacts the river discharge.

To further understand the behaviour of the Mestelá River in combination with the characteristics of the catchment, a FLEX-Topo model was developed. At this time, the model does not accurately illustrate the positive impact of cloud forests on the Mestelá River's base flow. The model's limitation in achieving a discharge match with observed data is primarily due to the constraints of limited measurements. A more refined and better-fitted model would require an extended forcing time series. However, the existing FLEX-Topo model serves as a strong foundation for future enhancements, particularly in addressing key aspects such as moisture buffer release and horizontal precipitation.

In terms of the model's value, the use of the FLEX-Topo model holds significant promise for stakeholder engagement in discussions regarding water security and cloud forest protection. With an improved model, it becomes feasible to decompose the modelled discharge, effectively showing how cloud forests contribute to a stable base flow. Furthermore, the model can be run with different scenarios, showcasing how land-use changes affect the river discharge. The ability to visually demonstrate the importance of cloud forest contribution to the Mestelá River's base flow is a powerful tool for consultative collaboration with the appropriate authorities.

Since CCFC is in a multi-stakeholder environment it was derived from the results the importance of top-down as well as bottom-up interventions. The mentioned consultative collaboration is one of the strategies concluded from the analysis focusing on effective stakeholder management and engagement. The challenges and strategies identified from the analysis showed a close link to the research question of the project. Such as the lack of data and knowledge, which proves the relevance of the canopy monitoring site. Next to that, the intervention related to the challenge of weak institutions is data-driven advocacy. Data-driven advocacy can help in initiating top-down initiatives. The developed hydrological model can serve as a tool to perform this advocacy.
To address the challenges lack of environmental awareness, conflicts of interest:direct benefit and community characteristics, the stakeholder management framework recommends implementing bottom-up interventions through community capacity building. The insights from the project's knowledge can guide

these efforts. To make these insights accessible and engaging, a comic is developed.

Considering these points, we must conclude that the research question could not be fully addressed. However, this project serves as a comprehensive foundation for future research, offering detailed explanations of all the steps, beginning with data collection, followed by modelling and analysis, and concluding with a recommendation of interventions regarding stakeholder engagement for CCFC. This strong foundation, coupled with extensive data analysis, will enable future researchers to fully address the research question.

7
Recommendations

Canopy Monitoring

- Installation of a relative humidity sensor at the measurement station would provide extra insight into the hydrological processes related to condensation, moisture recycling and fog interception.
- Improvements of the fog traps could be made to enhance fog interception. This can be done by adding an inner cylinder with fish wire to the already existing fog trap.
- Soil moisture data could be used to verify the soil moisture content recovery time. Moreover, when the FLEX-Topo model is expanded to a distributed model, the soil moisture data could be used as an input value.
- When using tipping buckets, the installation of filters is necessary to prevent clogging of the system. Especially in the case of the installation of a long-term station.
- Proximity and accessibility of a monitoring site should be taken into account when deciding on the location of a long-term measurement site.
- The construction and installation of a long-term measurement site in a cloud forest canopy can be physically challenging, therefore a team of persons is recommended for the installation of the station.
- Anti-vandalism and anti-theft of the site could be improved. This can be done by e.g. moving the HOBO-link higher into the tree. For this, the sensor cables should be extended.

Discharge Model

- The accuracy of the discharge computation could be further improved by using multiple pressure sensors in the same cross-section, at different water levels. Based on this, the shape of the logarithmic profile is improved.
- Regularly re-measure the cross-section between the bank due to changes in the morphology after storm events.
- The rating curve should be expanded with water level and discharge measurements, leading to an accurate power-law fit. Next, the rating curve fit can be used to estimate the discharge when measuring a water level. This results in a long-term measurement system where no expensive pressure sensors are involved, only the already constructed water level measuring pole.

Hydrological Model

- The FLEX-Topo model is currently only set up and run with the 20-day data. Normally, a hydrological model is trained with data from multiple years. It is recommended to first try to run the model with extra data before changing the structure and/or parameters in the model.
- When the FLEX-Topo model is reliable, it is possible to run the model with different scenarios such as deforestation versus reforestation. The outcome of the model can show the impact of the scenarios on the Mestelá River discharge.
- Next to that, it could be possible to further analyse periods of droughts and floods.

- A good method to analyse catchments and find patterns is to find hydrological signatures from the data series. Signatures such as the base flow index, declining limb density and the Budyko curve too name a few.
- It's also recommended to improve the method of calculating the goodness of fit with the objective function. Kling Gupta Efficiency is one that is being used more recently, but even a R^2 would be a good objective function, which is better at fitting peaks. Using the R^2 complementary to the NSE can be a very powerful method. This way, euclidean distance can be applied so as to find model parameter sets that respond well to both objective functions.
- Using several parameter sets as an 'envelope' is a better way to show how uncertainty propagates through the use of several models. The General Linear Unbiased Estimator (GLUE) is a method to could be used to showcase this uncertainty of the model results.
- The FLEX-Topo model currently contains 19 parameters. Normally, a model with a shorter range of data is tested with a simpler model using parameters to prevent over fitting. It is recommended to also look at the possibilities of a simpler model, as a complementary model to the FLEX-Topo model.
- Currently, some parameters are shared within the model, so as to decrease the total number of parameters. For further research, it is recommended to look critically at these groupings.
- Note is that this project used Monte Carlo simulation for parameter selection. This is an inefficient method for parameter sampling. We recommend exploring different sampling techniques, either stochastic or evolutionary strategies. Stochastic sampling techniques such as Latin Hypercube Sampling or Stratified sampling are better at the homogeneous exploration of the parameter space [44].
- Literary review from the previous Cloud Chasers group showed that the use of the FIESTA model is widespread for horizontal precipitation generation in TMCF's. The FIESTA model is able to generate oreographic influences. Due to time constraints and a lack of knowledge in remote sensing, the FIESTA model was not included. However, for a follow-up group that will focus more on the modelling side of the catchment, it is highly recommended to incorporate it in the model.
- With a well-fitted model, it becomes feasible to deconstruct how and which parts of the catchment contribute to the flow of the Mestelá River. Using model decomposition to show how cloud forest contribute to the base flow of the river is a visual method for cloud forest conservation advocacy.
- Expanding the study area to the Cahabón River Watershed instead of the Mestelá River would increase the socio-economic impact and relevance for stakeholders. The discharge could be computed at the weir near Cobán. However, this expansion would bring added complexities, such as data availability, collaboration with other institutions, and increased data variability.

References

[1] D. Arias et al. “Cloud Forest Hydrology in a Changing Context”. In: *Multidisciplinary Project* ().

[2] Author Not Available. *That Roof Over There Is Mine: Flooding in Remote Guatemala*. Accessed on: October 10, 2023. Dec. 2020. URL: https://www.aljazeera.com/features/2020/12/9/that-roof-over-there-is-mine-flooding-in-remote-guatemala.

[3] Jurjen Battjes and Robert Jan Labeur. *Unsteady Flow in Open Channels*. United Kingdom: Cambridge University Press, 2017.

[4] S. Bergström. “Development and application of a conceptual runoff model for Scandinavian catchments”. In: *RHO, Hydrology and Oceanography* 7 (1976).

[5] Adam Berland et al. “The role of trees in urban stormwater management”. In: *Landscape and Urban Planning* 162 (2017), pp. 167–177. ISSN: 0169-2046. DOI: https://doi.org/10.1016/j.landurbplan.2017.02.017. URL: https://www.sciencedirect.com/science/article/pii/S0169204617300464.

[6] Gina Berrones et al. “Assessment of fog gauges and their effectiveness in quantifying fog in the Andean páramo”. In: *Ecohydrology* 14.6 (2021), e2300. DOI: https://doi.org/10.1002/eco.2300. eprint: https://onlinelibrary.wiley.com/doi/pdf/10.1002/eco.2300. URL: https://onlinelibrary.wiley.com/doi/abs/10.1002/eco.2300.

[7] S. Brammer and A. Millington. “The Development of Corporate Charitable Contributions in the UK: A Stakeholder Analysis”. In: *Journal of Management Studies* 41.8 (2004), pp. 1411–1434.

[8] J. S. Brooks, K. A. Waylen, and M. Borgerhoff Mulder. “How National Context, Project Design, and Local Community Characteristics Influence Success in Community-Based Conservation Projects”. In: *Proceedings of the National Academy of Sciences* 109.52 (2012), pp. 21265–21270.

[9] L. A. Bruijnzeel. “Hydrological functions of tropical forests: Not seeing the soil for the trees?” In: vol. 104. Sept. 2004, pp. 185–228. DOI: 10.1016/j.agee.2004.01.015.

[10] L. A. Bruijnzeel. “Hydrology of tropical montane cloud forests: A Reassessment”. In: *Land Use and Water Resources Research* 1 (Jan. 2001).

[11] L.A. Bruijnzeel, F.N. Scatena, and L.S. Hamilton. *Tropical Montane Cloud Forests: Science for Conservation and Management*. Cambridge University Press, 2010.

[12] John M. Bryson. “What to Do When Stakeholders Matter”. In: *Public Management Review* 6.1 (2004), pp. 21–53. DOI: 10.1080/14719030410001675722.

[13] K. Buysse and A. Verbeke. “Proactive Environmental Strategies: A Stakeholder Management Perspective”. In: *Strategic Management Journal* 24.5 (2003), pp. 453–470.

[14] Gaylon S. Campbell. *The researcher’s complete guide to the Leaf Area index (LAI)*. N.D. URL: https://www.metergroup.com/en/meter-environment/education-guides/researchers-complete-guide-leaf-area-index-lai (visited on 10/23/2023).

[15] Ven Te Chow, David R. Maidment, and Larry W. Mays. *Applied Hydrology*. McGraw-Hill, Inc., 1988.

[16] Miriam Coenders-Gerrits. “The role of interception in the hydrological cycle”. In: (Jan. 2010).

[17] E. A. Coleman et al. “Stakeholder Engagement Increases Transparency, Satisfaction, and Civic Action”. In: *Proceedings of the National Academy of Sciences* 116.49 (2019), pp. 24486–24491.

[18] Community Cloud Forest Conservation. *Community Cloud Forest Conservation*. Retrieved October 23, 10 C.E. 2020. URL: https://cloudforestconservation.org/.

[19] Consejo Nacional de Áreas Protegidas – CONAP. *CONAP*. Retrieved October 23, 10 C.E. URL: https://conap.gob.gt/.

[20] Corps of Engineers. *Description of the Hydrologic Cycle*. URL: https://www.nwrfc.noaa.gov/info/water_cycle/hydrology.cgi#:~:text=Interception%20is%20the%20process%20of,such%20as%20rills%20and%20furrows..

[21] Hans De Bruijn and Ernst Ten Heuvelhof. *Management in Networks*. Routledge, 2018.

[22] J. DeLay. “Canopy Water Balance of an Elfin Cloud Forest at Alakahi, Hawai□i”. In: (2005).

[23] Gayathri K. Devia, B.P. Ganasri, and G.S. Dwarakish. “A Review on Hydrological Models”. In: *Aquatic Procedia* 4 (2015), pp. 1001–1007.

[24] Art Dewulf. “An Introduction to Multi-Actor Processes”. In: *Wicked Problems and Multi-Actor Domains*. Ed. by Barbara Gray. Adapted from Gray, 1985. 2007, pp. 1–15.

[25] H. Elsenbeer, D.K. Cassel, and L. Zuniga. “Throughfall in the Terra Firme Forest of Western Amazonia”. In: *Journal of Hydrology (New Zealand)* 32.2 (1994), pp. 30–44. ISSN: 00221708, 24633933. URL: http://www.jstor.org/stable/43944724 (visited on 10/12/2023).

[26] Bert Enserink et al. *Policy Analysis of Multi-Actor Systems*. 2nd. TU Delft OPEN Publishing, 2022. DOI: 10.5074/T.2022.004.

[27] ESA. *SENTINEL-2 MISSION GUIDE*. N.D. URL: https://sentinels.copernicus.eu/web/sentinel/missions/sentinel-2 (visited on 10/23/2023).

[28] Instituto Nacional de Estadistica Guatemala. “Resultados Censo 2018”. In: *Resultados del XII Censo Nacional de Población y VII de Vivienda* (2019).

[29] F. Fenicia et al. “Understanding catchment behavior through stepwise model concept improvement”. In: *Water resources research* 44 (2008).

[30] A.L. Franklin. “Introduction to Stakeholder Engagement”. In: *Stakeholder Engagement*. Springer, Cham, 2020. DOI: 10.1007/978-3-030-47519-2_1.

[31] R. E. Freeman. “Stakeholder Management and Reputation”. In: *I. Ethics in a Global World* (2014), p. 363.

[32] Arnoud Frumau et al. “Fog gauge performance under conditions of fog and wind-driven rain. In: Tropical Montane Cloud Forests: Science for Conservation and Management”. In: Feb. 2011, pp. 293–301. ISBN: Online ISBN:9780511778384. DOI: 10.1017/CBO9780511778384.032.

[33] S. Gao et al. “Testing the realism of a topography-driven model (FLEX-Topo) in the nested catchments of the Upper Heihe, China”. In: *Hydrology and Earth System Sciences* 18 (2014), pp. 1895–1915.

[34] C. F. Gaymer et al. “Merging Top-Down and Bottom-Up Approaches in Marine Protected Areas Planning: Experiences from Around the Globe”. In: *Aquatic Conservation: Marine and Freshwater Ecosystems* 24.S2 (2014), pp. 128–144.

[35] Sybil Gotsch, Nalini Nadkarni, and Autumn Amici. “The functional roles of epiphytes and arboreal soils in tropical montane cloud forests”. In: *Journal of Tropical Ecology* -1 (July 2016), pp. 1–14. DOI: 10.1017/S026646741600033X.

[36] James L. Guernsey. *Orographic precipitation*. Boston, MA: Springer US, 1987, pp. 643–643. ISBN: 978-0-387-30749-7. DOI: 10.1007/0-387-30749-4_128. URL: https://doi.org/10.1007/0-387-30749-4_128.

[37] B. Gurung and A. Thapa. “Exploring the Impact of Community Engagement, Including Mental Health, on the Efficacy of Environmental Education and Biodiversity Conservation: A Systematic Literature Review”. In: *Journal of Empirical Social Science Studies* 7.4 (2023), pp. 16–50.

[38] Hawaii. *Cloud Water Interception*. 2018. URL: https://www.hawaii.edu/climate-data-portal/cloud-water-interception-in-hawaii/ (visited on 10/2023).

[39] Reg Herschy. “The stage-discharge relation”. In: (1993).

[40] J. Hogan, P. Dolan, and P. Donnelly. *Approaches to Qualitative Research: Theory and its Practical Application*. Retrieved from The University of Phoenix eBook Collection. Cork, Ireland: Oak Tree Press, 2009.

[41] Curtis D. Holder. “The hydrological significance of cloud forests in the Sierra de las Minas Biosphere Reserve, Guatemala”. In: *Geoforum* 37 (1 Jan. 2006), pp. 82–93. ISSN: 00167185. DOI: 10.1016/j.geoforum.2004.06.008.

[42] J. R. Hollyer. “Is it Better to Empower the People or the Authorities? Assessing the Conditional Effects of “Top-Down” and “Bottom-Up” Anticorruption Interventions”. In: *New Advances in Experimental Research on Corruption*. Vol. 15. Emerald Group Publishing Limited, 2012, pp. 247–277.

[43] B. Hounslow. “Community Capacity Building Explained”. In: *Stronger Families Learning Exchange Bulletin* 1.1 (2002), pp. 20–22.

[44] Markus Hrachowitz. *Lecture notes in River Basin Hydrology and Water management, unit 3: models, lecture 4: Equifinality and Distributed Models*. Mar. 2023.

[45] Instituto Nacional de Bosques - INAB. *INAB*. Retrieved October 23, 10 C.E. URL: https://www.inab.gob.gt/.

[46] Takayuki Ito et al., eds. *Innovations in Agent-Based Complex Automated Negotiations*. Vol. 319. Springer, 2010.

[47] Shazia Jamshed. “Qualitative Research Method-Interviewing and Observation”. In: *Journal of Basic and Clinical Pharmacy* 5.4 (2014), p. 87.

[48] N. Jeffery. “Stakeholder Engagement: A Road Map to Meaningful Engagement”. In: *Doughty Century, Cranfield School of Management* (2009). URL: https://dspace.lib.cranfield.ac.uk/bitstream/1826/3801/3/Stakeholder_engagement-2009.pdf.

[49] G. Johnson and K. Scholes. *Exploring Corporate Strategy (6th edn)*. Harlow, England: Pearson Education, 2002.

[50] K. E. Joyce and N. Cartwright. “Bridging the Gap Between Research and Practice: Predicting What Will Work Locally”. In: *American Educational Research Journal* 57.3 (2020), pp. 1045–1082. DOI: 10.3102/0002831219866687.

[51] George Kassinis and Nikos Vafeas. “Stakeholder Pressures and Environmental Performance”. In: *Academy of Management Journal* 49.1 (2006), pp. 145–159.

[52] E. Knott et al. “Interviews in the Social Sciences”. In: *Nature Reviews Methods Primers* 2.1 (2022), p. 73.

[53] Steinar Kvale. “Ten Standard Objections to Qualitative Research Interviews”. In: *Journal of Phenomenological Psychology* 25.2 (1994), pp. 147–173. DOI: 10.1163/156916294X00016.

[54] H. van der Kwast. *PCRaster Tools*. URL: https://plugins.qgis.org/plugins/pcraster_tools/ (visited on 10/13/2023).

[55] A. LaBastille and D.J. Pool. “On the Need for a System of Cloud-Forest Parks in Middle America and the Caribbean”. In: *Environmental Conservation* 5.3 (1978), pp. 183–190.

[56] C. R. Larrison. “A Comparison of Top-Down and Bottom-Up Community Development Interventions in Rural Mexico: Practical and Theoretical Implications for Community Development Programs”. University of Georgia, 1999.

[57] Wenjie Liu et al. “On the relationship between forests and occult precipitation (dew and fog precipitation)”. In: *Journal of Natural Resources* 16 (Jan. 2001), pp. 571–575.

[58] Zhaofei Liu et al. *Conceptual Hydrological Models*. Ed. by Qingyun Duan et al. Berlin, Heidelberg: Springer Berlin Heidelberg, 2017, pp. 1–23. ISBN: 978-3-642-40457-3. DOI: 10.1007/978-3-642-40457-3_22-1. URL: https://doi.org/10.1007/978-3-642-40457-3_22-1.

[59] Richard Lloyd. “The Role of NGO Self-Regulation in Increasing Stakeholder Accountability”. In: *One World Trust* 1 (2005), p. 15.

[60] Tadeusz Magiera et al. “Magnetic susceptibility as indicator of anthropogenic disturbances in forest topsoil: A review of magnetic studies carried out in Central European forests”. In: *Ecological Indicators* 106 (2019), p. 105518. ISSN: 1470-160X. DOI: https://doi.org/10.1016/j.ecolind.2019.105518. URL: https://www.sciencedirect.com/science/article/pii/S1470160X19305035.

[61] Larry W. Mays. *Water Resources Engineering*. 2nd ed. John Wiley and Sons, Inc., 2011.

[62] S. McCulloch-Jones et al. "Exploring the Alignment Between the Bottom-Up and Top-Down Objectives of a Landscape-Scale Conservation Initiative". In: *Environmental Conservation* 48.4 (2021), pp. 255–263.

[63] MINEDUC. *Ministerio De Educación*. Retrieved October 23, 10 C.E. 2021. URL: https://www.mineduc.gob.gt.

[64] MINEDUC - DIDEDUC Alta Verapaz. *Ministerio De Educación*. Retrieved October 23, 10 C.E. URL: https://www.mineduc.gob.gt/AltaVerapaz/.

[65] J. Ninan and N. Sergeeva. "Mobilizing Megaproject Narratives for External Stakeholders: A Study of Narrative Instruments and Processes". In: *Project Management Journal* 53.5 (2022), pp. 520–540.

[66] G. AH. Nonet, T. Gössling, R. Van Tulder, et al. "Multi-stakeholder Engagement for the Sustainable Development Goals: Introduction to the Special Issue". In: *J Bus Ethics* 180 (2022), pp. 945–957. DOI: 10.1007/s10551-022-05192-0.

[67] A. Noya and E. Clarence. *Community Capacity Building: Fostering Economic and Social Resilience*. Organisation for Economic Cooperation and Development, 2009, pp. 26–27.

[68] O. et al. "Climatic Impact of Tropical Lowland Deforestation on Nearby Montane Cloud Forests". In: *Science* 294.5542 (2001), pp. 584–587.

[69] Christopher J. O'Bryan et al. "Setting Conservation Priorities in Multi-Actor Systems". In: *BioScience* 73.7 (July 2023), pp. 522–532. DOI: 10.1093/biosci/biad046.

[70] Observatorio Regional de Planificación para el Desarrollo. *Consejos Comunitarios de Desarrollo Urbano y Rural (COCODE) de Guatemala*. Retrieved October 23, 10 C.E. URL: https://observatorioplanificacion.cepal.org.

[71] Juliet M. S. Oktay. *Grounded Theory*. United Kingdom: Oxford University Press, USA, 2012.

[72] Oregon State University. *Community-Based Interventions*. URL: https://health.oregonstate.edu/hallie-ford.

[73] R. Pirard et al. *Effectiveness of Forest Conservation Interventions: An Evidence Gap Map*. Tech. rep. IEU Learning Paper, 2019. URL: https://ciforicraf.wpexpert.id/knowledge/publication/7463.

[74] Victor M. Ponce. *The psychrometric constant*. 2014. URL: https://ponce.sdsu.edu/psychrometric_constant.html (visited on 10/17/2023).

[75] I. Pope et al. "Deforestation of montane cloud forest in the Central Highlands of Guatemala: Contributing factors and implications for sustainability in Q'eqchi' communities". In: *International Journal of Sustainable Development and World Ecology* 22 (3 May 2015), pp. 201–212. ISSN: 17452627. DOI: 10.1080/13504509.2014.998738.

[76] Ian Pope et al. "Cloud Forest Conservation in the Central Highlands of Guatemala Hinges on Soil Conservation and Intensifying Food Production". In: *The Professional Geographer* 68 (Mar. 2015), pp. 1–13. DOI: 10.1080/00330124.2015.1006556.

[77] Hanafi Radwan. *crop water rquiment*. Jan. 1977.

[78] C. Ramis, R. Romero, and Alonso S. *Relative humidity*. URL: https://meteorologia.uib.eu/ROMU/formal/relative_humidity/relative_humidity.pdf (visited on 10/24/2023).

[79] D. K. Ray. "Tropical Montane Cloud Forests". In: *Climate Vulnerability: Understanding and Addressing Threats to Essential Resources* 5 (2013), pp. 79–85. DOI: 10.1016/B978-0-12-384703-4.00519-0.

[80] M. S. Reed et al. "Mediation and Conservation Conflicts: From Top-Down to Bottom-Up". In: *Conflicts in Conservation: Navigating Towards Solutions*. Ecological Reviews. Cambridge University Press, 2015, pp. 226–239.

[81] Stefan C. Renner, Melanie Voigt, and Michael Markussen. "Regional Deforestation in a Tropical Montane Cloud Forest in Alta-Verapaz, Guatemala". In: *Ecotropica* 12 (2006), pp. 43–49.

[82] Axel Ritter, Carlos M. Regalado, and Juan Carlos Guerra. "Quantification of Fog Water Collection in Three Locations of Tenerife (Canary Islands)". In: *Water* 7.7 (2015), pp. 3306–3319. ISSN: 2073-4441. DOI: 10.3390/w7073306. URL: https://www.mdpi.com/2073-4441/7/7/3306.

[83] S. M. Robinson. "Collaborative Consultation". In: *Learning about Learning Disabilities*. Academic Press, 1991, pp. 441–463.

[84] Victoria Rodriguez. "Cloud Forest Conservation and Hydrological Services in Guatemala". In: *Forest Ecology and Management* 432 (2019), pp. 778–789.

[85] J. Roloff. "Learning from Multi-stakeholder Networks: Issue-focused Stakeholder Management". In: *Journal of Business Ethics* 82 (2008), pp. 233–250.

[86] R. M. Sail and A. Abu-Samah. "Community Development Through Community Capacity Building: A Social Science Perspective". In: *Journal of American Science* 6.2 (2010), pp. 68–76.

[87] H.H.G. Savenije. "Topography driven conceptual modelling (FLEX-Topo)". In: *Hydrology and Earth System Sciences* 14 (2010), pp. 2681–2692.

[88] G. Steiner. "Supporting Sustainable Innovation Through Stakeholder Management: A Systems View". In: *International Journal of Innovation and Learning* 5.6 (2008), p. 595. DOI: 10.1504/ijil.2008.019143.

[89] Thunder Said Energy: The research consultancy for energy technologies. *Albedo of different landscapes: a challenge for reforestation?* URL: https://thundersaidenergy.com/downloads/albedo-of-different-landscapes-a-challenge-for-reforestation/ (visited on 10/17/2023).

[90] O. Tetens. "Über einige meteorologische Begriffe". In: *Geophys* 6 (1930), pp. 297–309.

[91] Andrée J. Tuzet. "Stomatal Conductance, Photosynthesis, and Transpiration, Modeling". In: *Encyclopedia of Agrophysics*. Ed. by Jan Gliński, Józef Horabik, and Jerzy Lipiec. Dordrecht: Springer Netherlands, 2011, pp. 855–858. ISBN: 978-90-481-3585-1. DOI: 10.1007/978-90-481-3585-1_213. URL: https://doi.org/10.1007/978-90-481-3585-1_213.

[92] UN.ESCAP. *Training Reference Material: Effective Stakeholder Engagement for the 2030 Agenda*. 2018. URL: https://hdl.handle.net/20.500.12870/105.

[93] VanEssen. *Project manuel Diver*. 2016. URL: https://www.vanessen.com/wp-content/uploads/2023/07/TD-Diver-DI8xx-ProductManual-en.pdf (visited on 10/17/2023).

[94] Juan Manuel Vargas, Francisco Pérez-Arce, and Salvador Valdés-Prieto. "Spatial Analysis of Poverty in Guatemala: The Case of Alta Verapaz Department". In: *Economía, Sociedad y Territorio* 16.51 (2016), pp. 291–322.

[95] E. J. Veneklaas et al. "Hydrological properties of the epiphyte mass of a montane tropical rain forest, Colombia". In: *Vegetatio* 89 (2 Oct. 1990), pp. 183–192. ISSN: 00423106. DOI: 10.1007/BF00032170/METRICS. URL: https://link.springer.com/article/10.1007/BF00032170.

[96] P. Weretecki, G. Greve, and J. Henseler. "Experiential Value in Multi-Actor Service Ecosystems: Scale Development and its Relation to Inter-Customer Helping Behavior". In: *Frontiers in Psychology* 11 (2021), p. 593390.

[97] Jerry Westerweel, Bendiks J Boersma, and Frans TM Nieuwstadt. *Turbulence: Introduction to Theory and Applications of Turbulent Flows*. Springer International Publishing, 2016.

[98] Worldbank. *Biodiversity Conservation and Sustainable Management of Living Natural Resources*. First. Environmental and Social Framework for IPF Operations. 2018.

[99] Worldbank. *Guatemala Sustainable Forest Management Project: Proposal for Operation Development*. Tech. rep. Unpublished document. n.d.

[100] WUR. "Calculation of the potential evaporation". In: URL: https://edepot.wur.nl/183107.

[101] Lincoln Zotarelli et al. "Step by Step Calculation of the Penman-Monteith Evapotranspiration (FAO-56 Method)". In: 2015. URL: https://api.semanticscholar.org/CorpusID:130168866.

A

Classification Figures

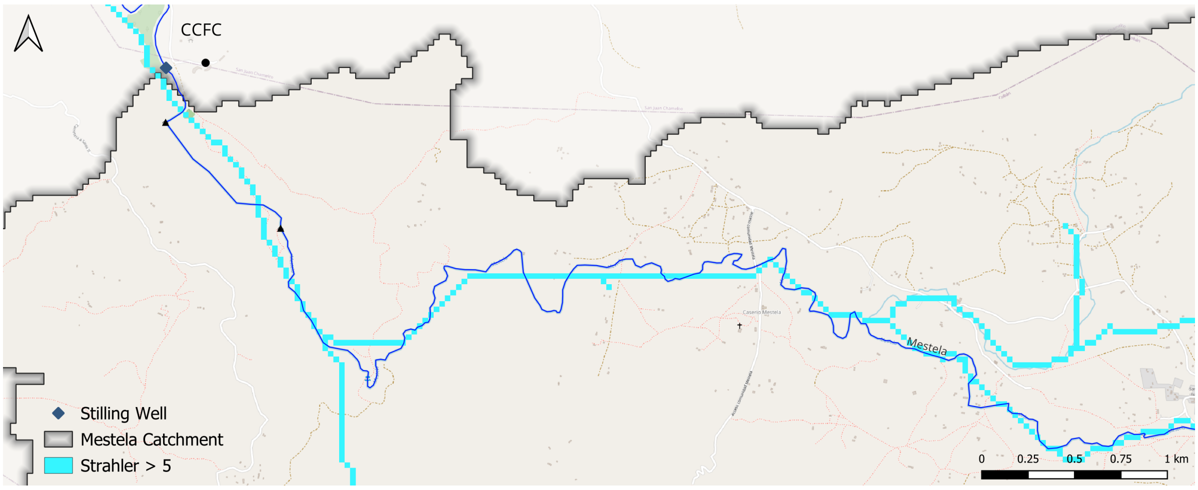
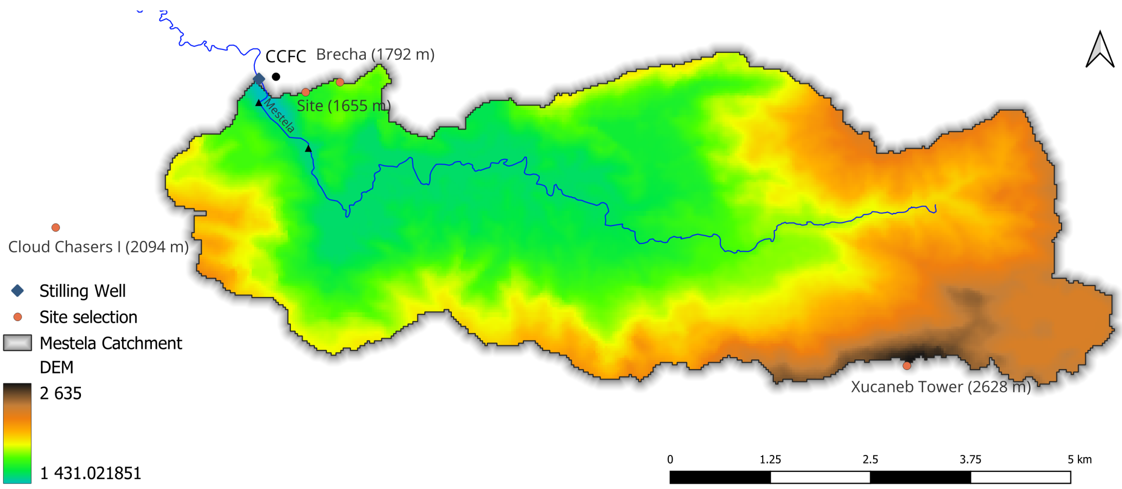
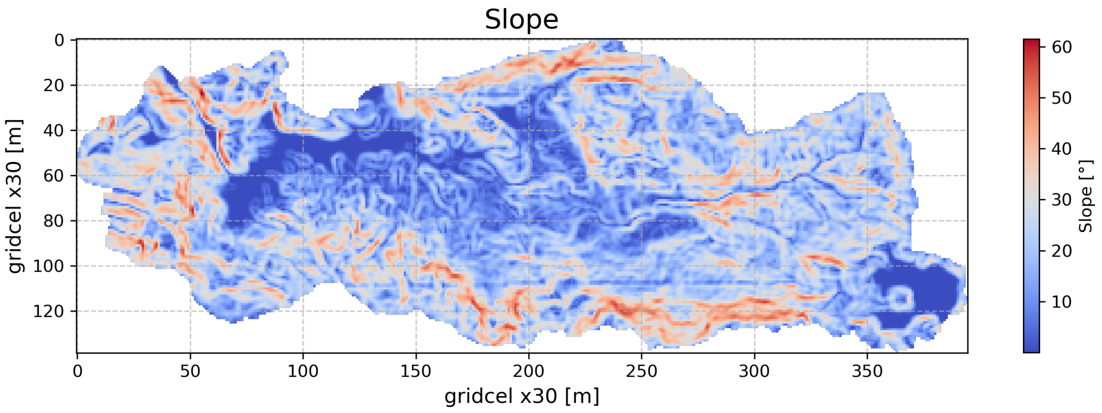


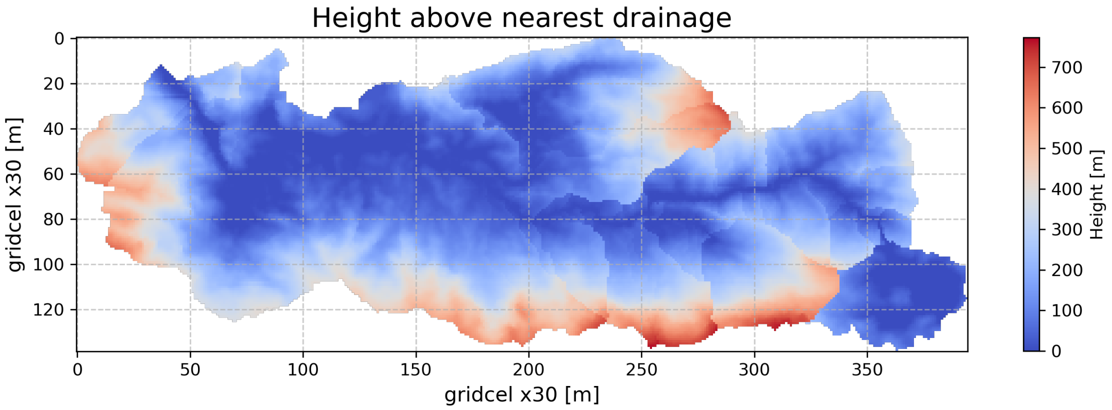
Figure A.1: Strahler stream flow visualisation

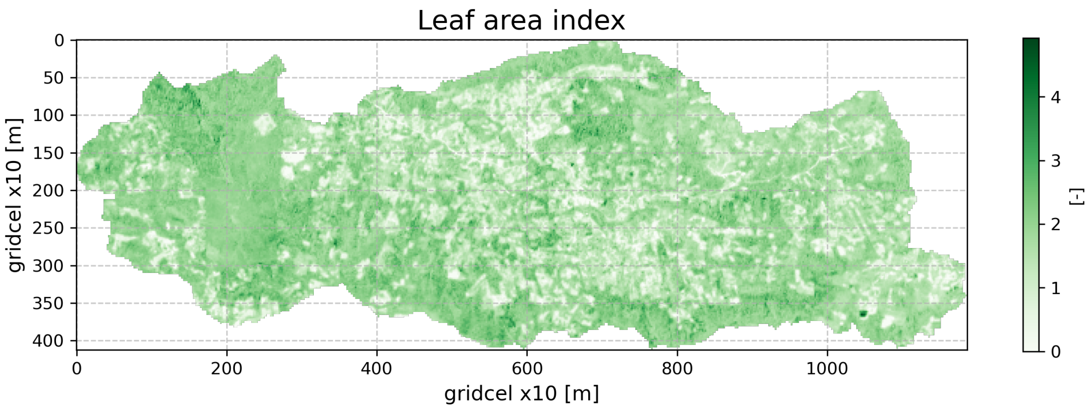


Listing A.1: Python code for landscape classification

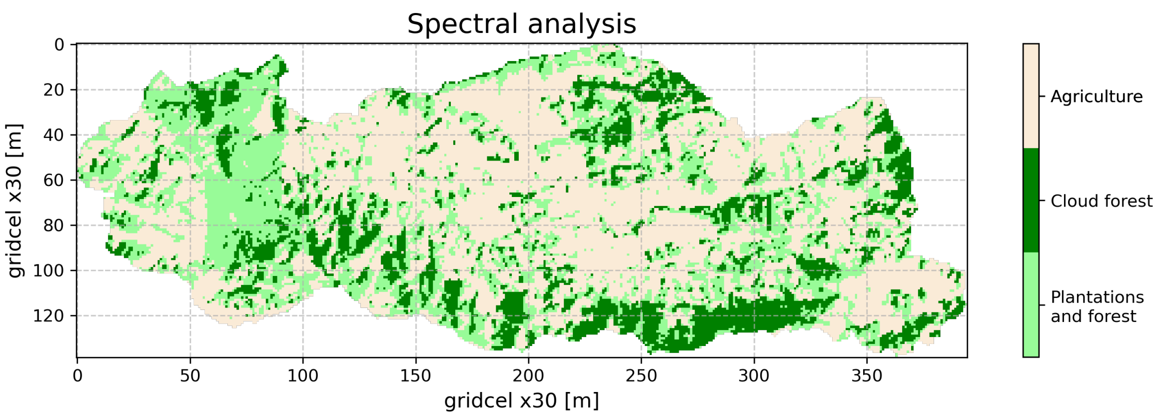
```python
# Make landscape classification
plateau = (np.array(hand) > 8) & (np.array(resized_LAI) <= 1.8)
```







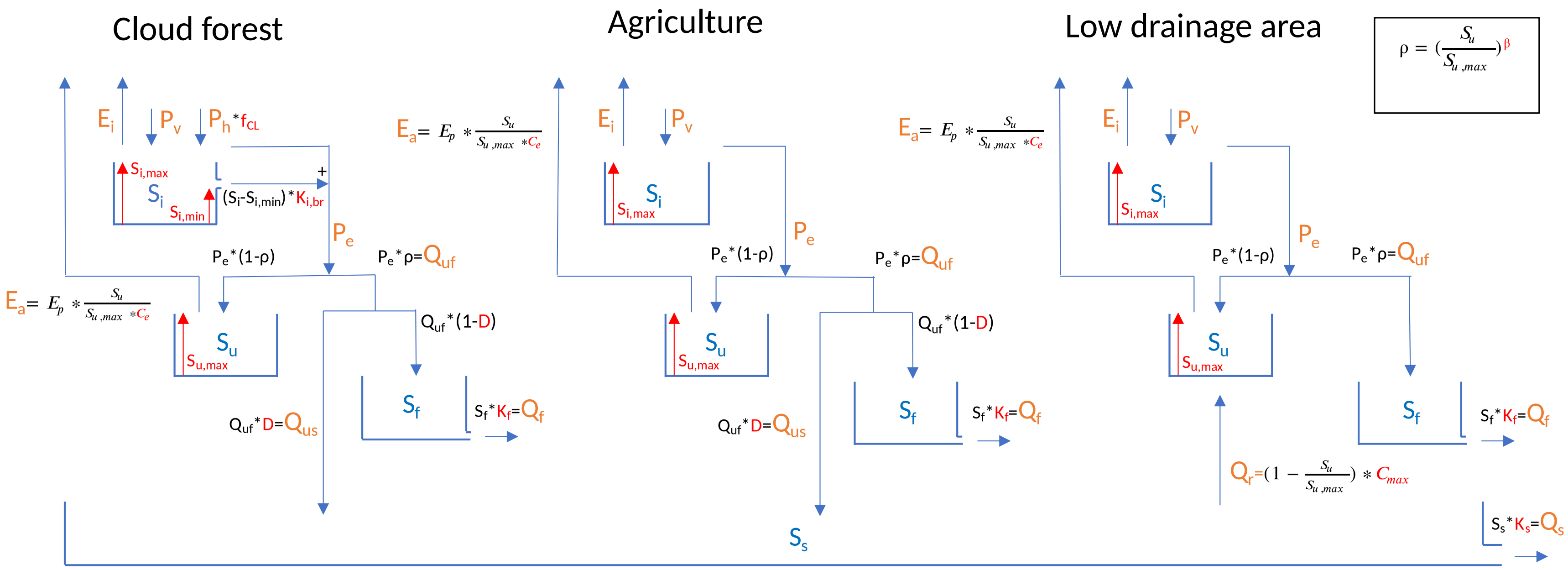

```
cloud_forest = (np.array(hand) > 8) & (np.array(resized_LAI) > 1.8)
wetland = np.array(hand) <= 8
basin = np.array(np.array(slope) >= 0, dtype=int)

# Matrics with landscape classes
nrows, ncols = basin.shape
landscapes = np.zeros((nrows, ncols))
landscapes[plateau] = 1
landscapes[cloud_forest] = 2
landscapes[wetland] = 3
```




```

# Plot landscapes
bounds = [1, 2, 3, 4]
clrs = ['palegreen', 'green', 'blue', 'blue']
cmap, norm = colors.from_levels_and_colors(bounds, clrs, extend='max')

plt.figure(figsize=(10, 6))
plt.imshow(landscapes, cmap=cmap, norm=norm)  # Adjust aspect ratio
plt.xlabel('gridcel x30 [m]', fontsize=12)
plt.ylabel('gridcel x30 [m]', fontsize=12)
plt.title('Landscape classification', fontsize=16)

# Create a custom colorbar
cbar = plt.colorbar(orientation='vertical', shrink=0.45, extend='neither')
cbar.set_ticks([1.5, 2.5, 3.5, 3.5])  # Set tick locations to match levels
cbar.set_ticklabels(['Agriculture', '(cloud) Forest', '', 'Wetlands'])  # Set tick labels

plt.tight_layout()
plt.grid(True, linestyle='--', alpha=0.7)
plt.savefig('Model_classification.png', dpi=300, transparent=True)
plt.show()
```

B

FLEX-Topo flowchart



C

Correction Factors

C.0.1. Throughfall

The surface area of the throughfall gutters is exactly 1 m^2. The unit of the tipping bucket is in mm/m^2 and is based on the area of the collection funnel, which is 214 cm^2. So, the collection funnel is approximately 47 times smaller than the collection area of the throughfall gutter. This means that the measured mm throughfall in the system should be corrected. The correction factor of the measured throughfall is the fraction of the collection area of the tipping bucket and the collection area of the throughfall, as is shown in Equation C.1.

$$\text{Correction Factor}_\mathbf{T} = \frac{\text{A}_\text{tippingbucket}}{\text{A}_\text{throughfall}} = \frac{214 * 10^{-4}}{1} = 0.0214 \tag{C.1}$$

C.0.2. Fog Traps

The amount of fog intercepted by the fog traps needs to be rewritten to the amount of horizontal precipitation in mm units. The vertical, cross-sectional area of the fog traps determines the amount of fog that can be intercepted. This cross-sectional area is 920 cm^2 per fog trap. The number of fog traps is 3. The collection area of the tipping bucket is 214 cm^2, just as explained in C.0.1. The resulting correction factor for the fog traps is shown in Equation C.2.

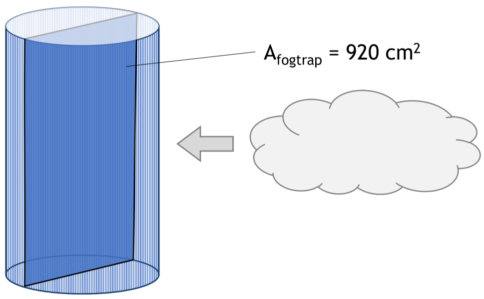


Figure C.1: Cross-section of 1 fog trap.

$$\text{Correction Factor}_\mathbf{F} = \frac{\text{A}_\text{tippingbucket}}{\text{A}_\text{fog traps}} = \frac{214 * 10^{-4}}{3 * 920 * 10^{-4}} = 0.0775 \tag{C.2}$$

D

Sensor and Station Specifications

Table D.1: Specifications of the sensors and stations.

	Tipping bucket	**Soil moisture sensor**	**HOBO station**
Formal name	Rain Gauge Smart Sensor	10HS Soil Moisture Smart Sensor	HOBO Remote Monitoring station
Model name	S-RGF-M002	S-SMD-M005	RX3000
Measurement range	0-10.2 cm per hour	0 to 0.570 m^3/m^3	
Resolution	0.2 mm	0.0008 m^3/m^3 (0.08%)	

E

Psychrometric Chart

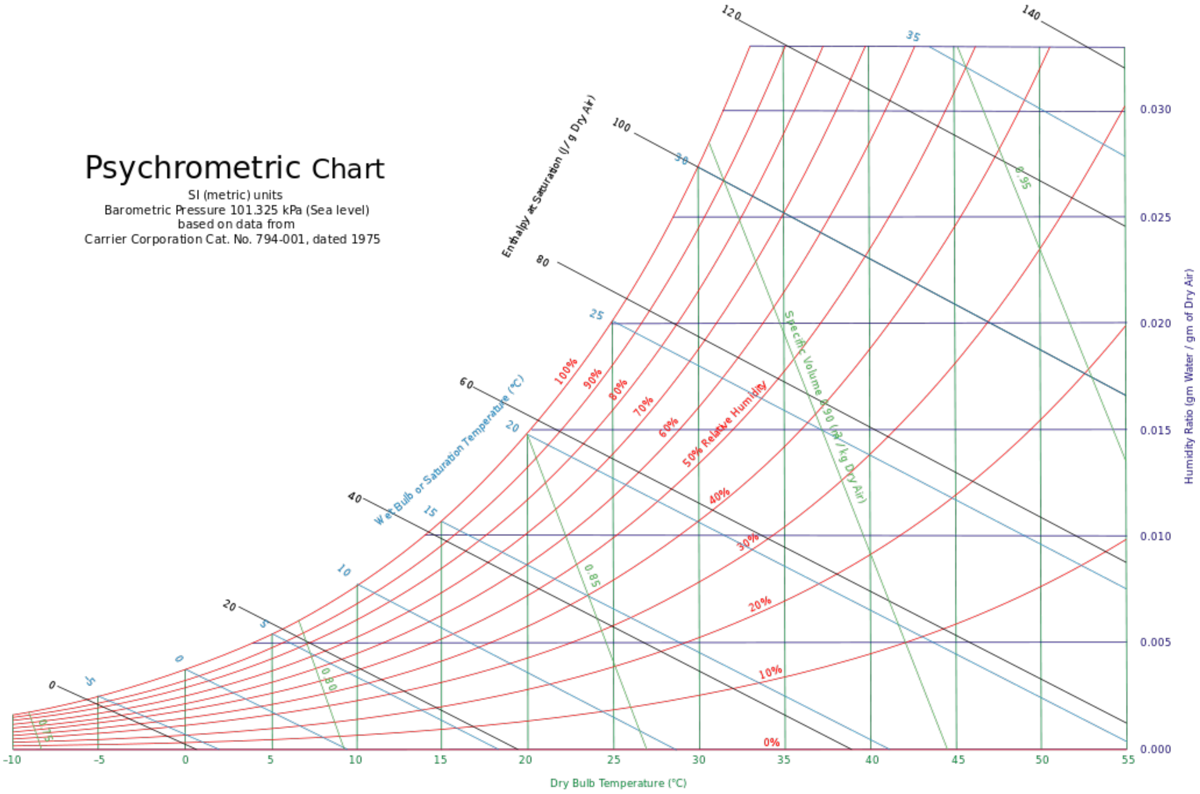


Figure E.1: Psychrometric chart displaying the relation between temperature, relative humidity and specific humidity.

F
Additional Data and Plots Related to Hydrological Processes

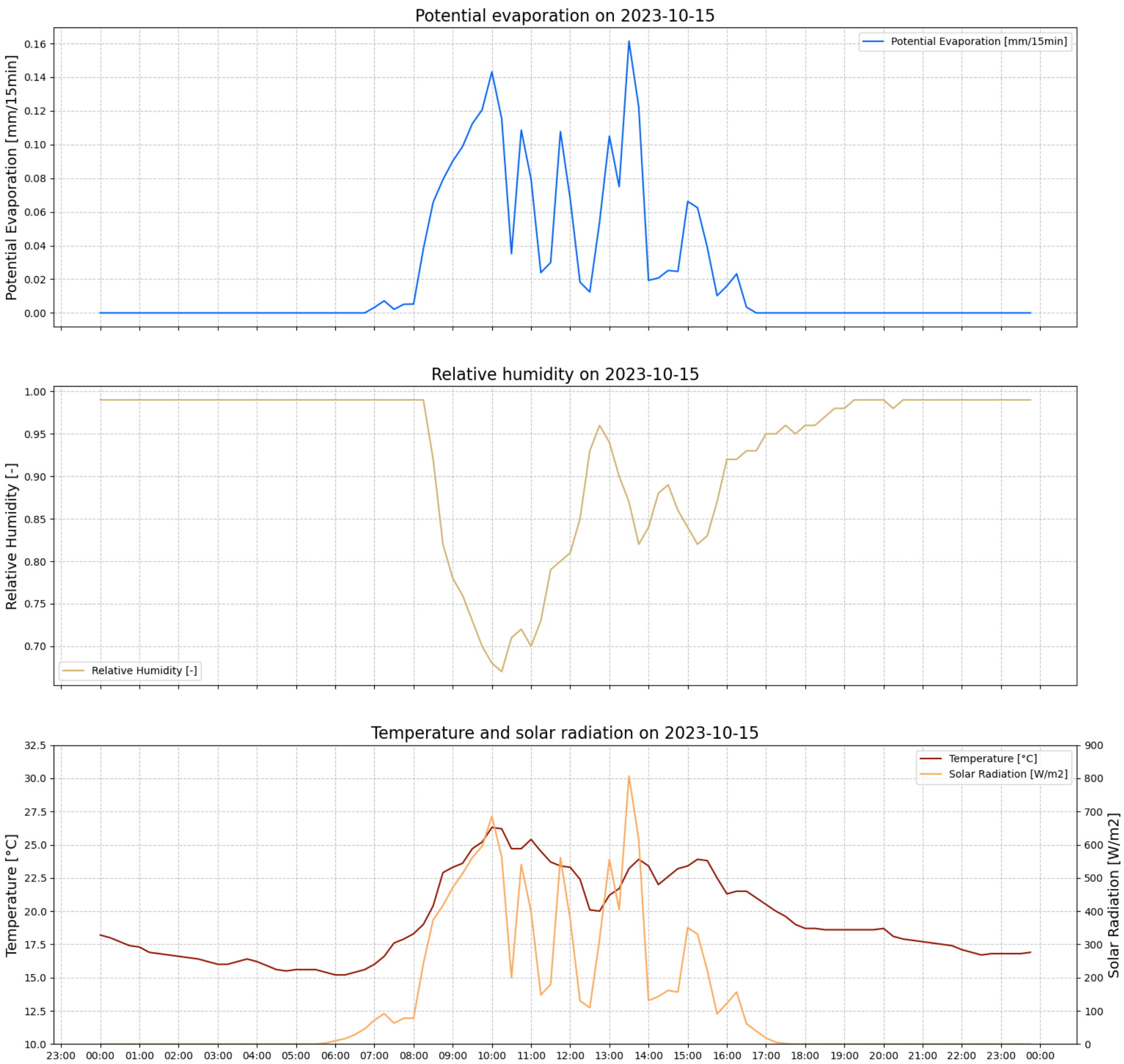


Figure F.1: Detailed plot of the evaporation, relative humidity, temperature and solar radiation on 15-10-2023

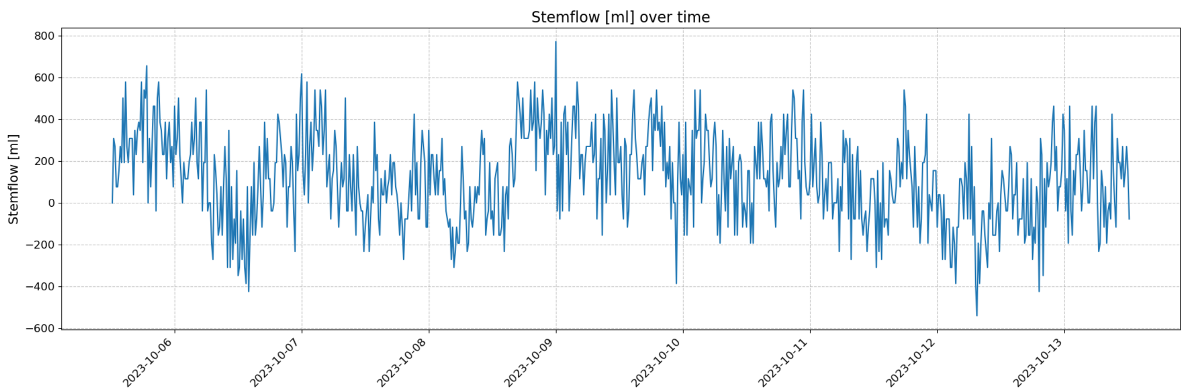


Figure F.2: Water level measured in the collection bottle of the stemflow. The volume of the collection bottle is 18.9 L, which was too big because significant evaporation occurred.

G Monte Carlo Parameter Visualisation

Table G.1: Parameters from the Monte Carlo simulation. With the 15 minute using in total 1.000.000 simulations, whilst the other runs used 100.000 simulations. Class names: C stands for Cloud forest, A for Agriculture and W for Wetland.

Parameter	Class	15 min	15 min altered	1 hour	1 hour altered
f_{CL}	C	3.18E-4	4.22E-4	5.14E-3	7.833E-2
K_s	C	1.40E-5	1.521E-5	7E-6	5.2E-5
T_{lag}	C	205.613	159.4	267.051	41.576
C_e	W	0.775	0.852	0.726	0.831
C_e	A, CL	0.224	0.229	0.156	0.898
$S_{u,max}$	W	78.151	126.2	79.269	105.863
$S_{u,max}$	A, CL	7.091	14.25	15.100	8.513
β	W	0.530	0.386	4.598	4.138
β	A, CL	4.997	5.267	4.301	3.883
C_{max}	W	0.437	0.761	0.413	0.484
K_f	W	2.5E-5	5.412E-5	8.4E-5	1.42E-4
K_f	A, CL	1.23E-4	1.412E-4	1.14E-4	5.92-4
I_{max}	W	25.575	17.16	25.733	14.832
I_{max}	A	17.655	8.460	15.224	5.436
I_{max}	CL	18.351	28.54	34.479	37.733
I_{min}	CL	2.217	2.49	2.983	1.629
D	A	0.868	0.898	0.847	0.209
D	CL	0.773	0.921	0.921	0.665
$K_{i,BR}$	CL	2.56E-2	1.09E-2	9.3E-3	6.412E-2
NSE	-	0.076	-0.390	0.281	-0.056

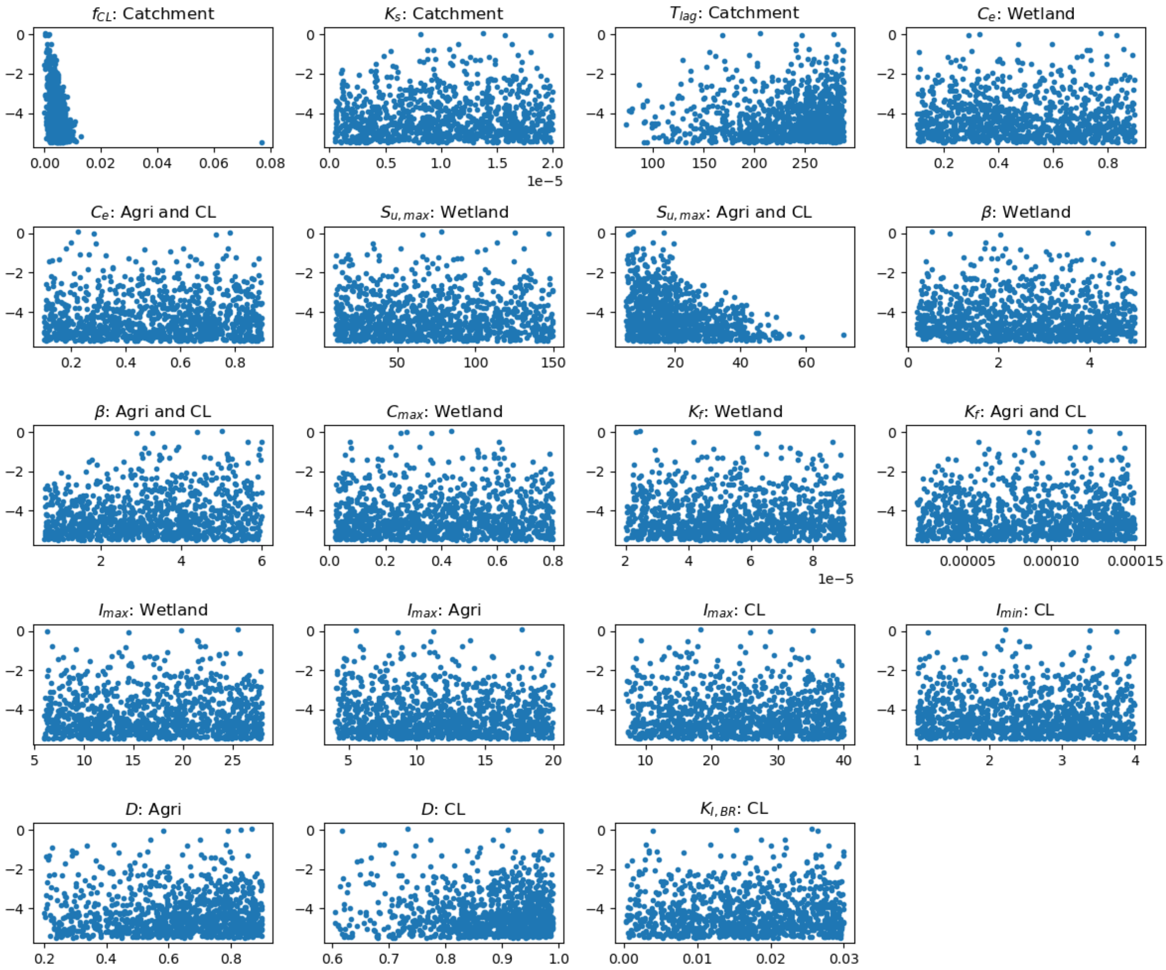


Figure G.1: Results of the 15-minute time step's 0.1% best parameter plots. The original parameter space is specified in Table 3.10. The y-axis displays the NSE coefficient.

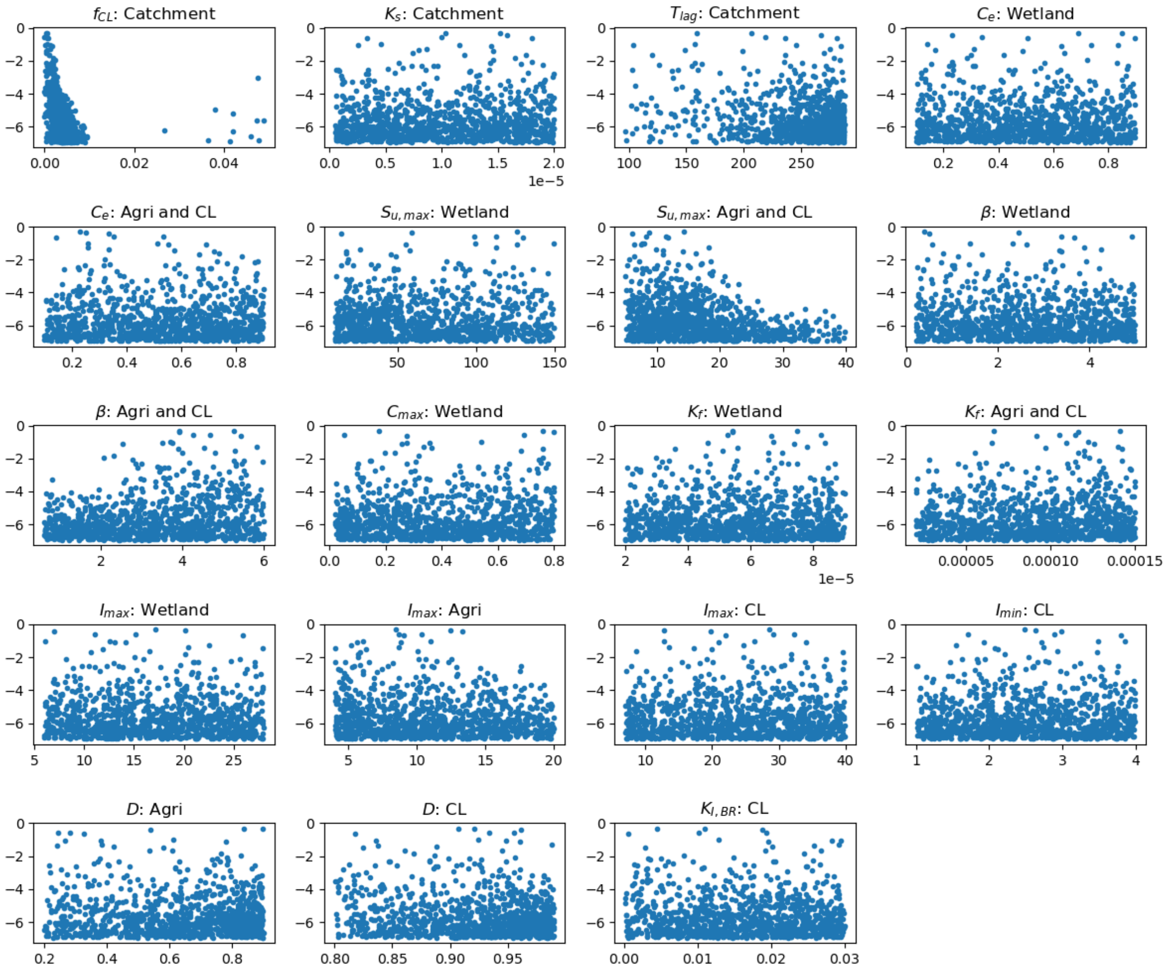


Figure G.2: Results of the altered 15-minute time step's 1% best parameter plots. The original parameter space is specified in Table 3.10. The y-axis displays the NSE coefficient.

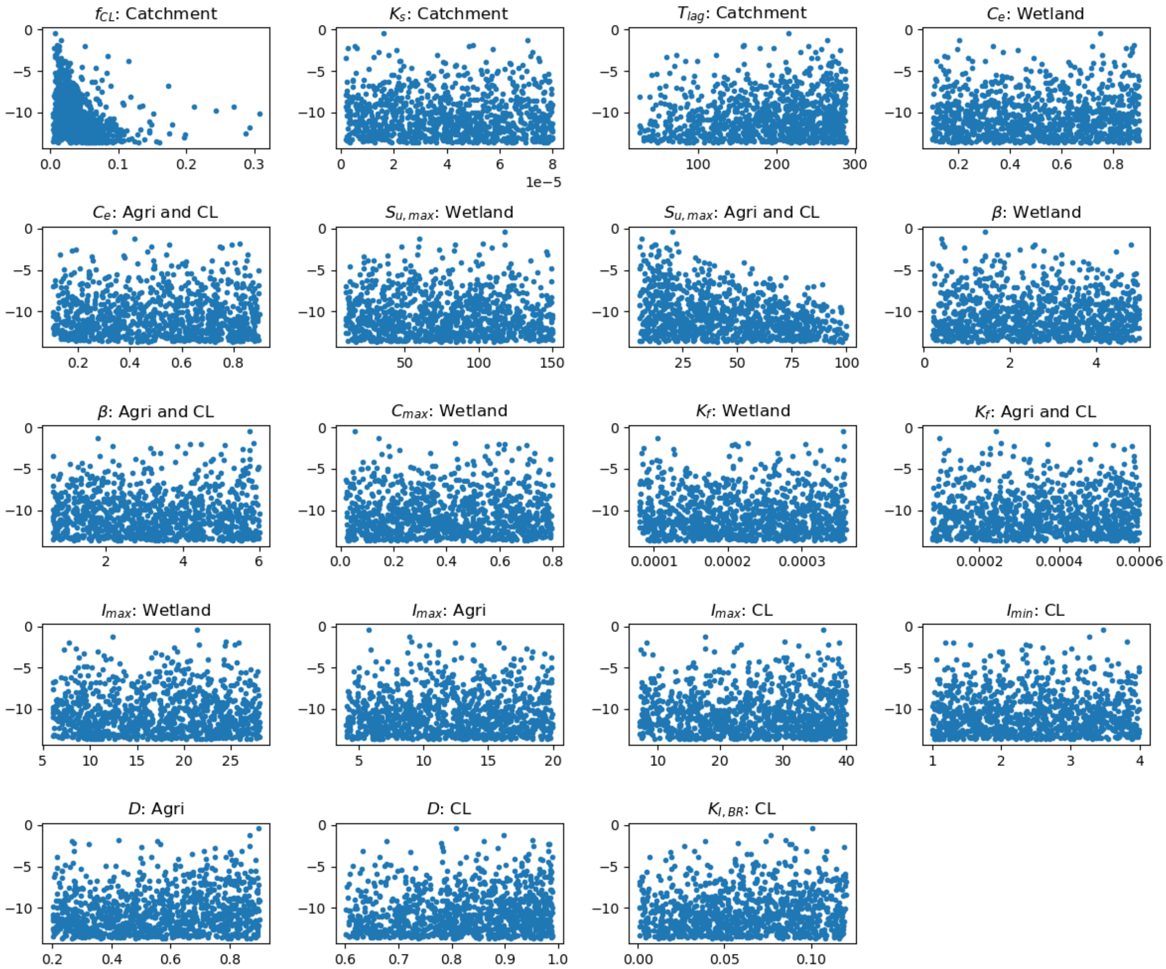


Figure G.3: Results of the 1 hour time step's 1% best parameter plots. Note that the parameter range for the parameters f_{CL}, K_s, K_f (both for W and for A+CL) and $K_{i,BR}$ were multiplied by four to account for the increase in timestep. The original parameter space is specified in Table 3.10. The y-axis displays the NSE coefficient.

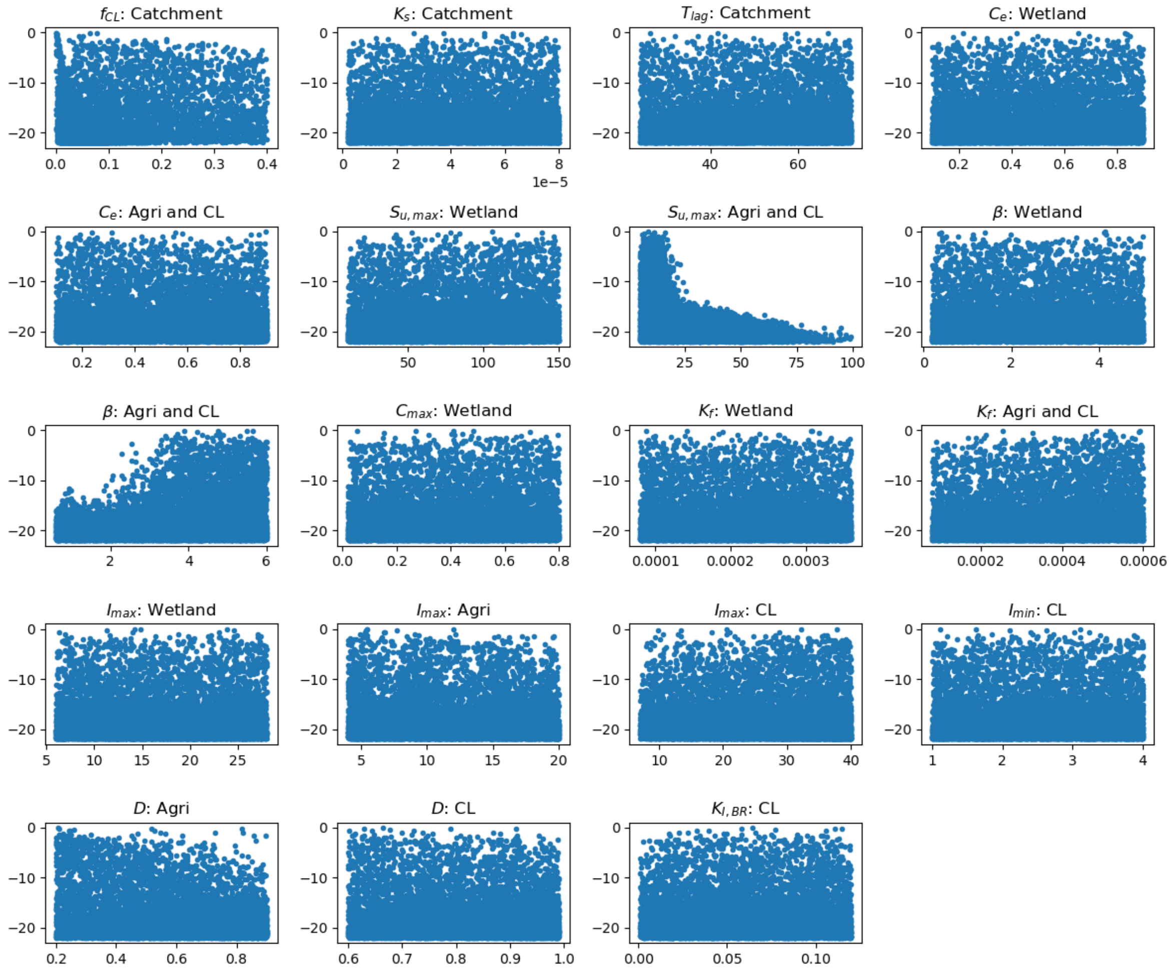


Figure G.4: Results of the 1 hour time step's 1% best parameter plots, for the altered dataset. The y-axis displays the NSE coefficient.

H

Interviews Table

Table H.1: Table including specifications of the interviews.

No	Date	Organisation / Designation
1	1-10	*NGO CCFC* Owner
2	1-10	*NGO CCFC* Co-owner
3	3-10	*Local university* Professor Hydrology
4	4-10	*Cloud forest nature reserve* Owner and Conservation specialist
5	4-10	*Nature reserve* Owner and Conservation specialist
6	5-10	*NGO Fundaeco* Conservation science strategies advisor
7	5-10	Student Local Environmental Management
8	6-10	Researcher: specialised in conservation and community engagement
9	8-10	*Non-local university* Professor Forest ecophysiology and canopy scientist
10	9-10	Researcher: specialised Mayan Q'eqchi' communities and agriculture
11	9-10	Local farmer of larger parcel
12	10-10	Local resident Q'eqchi' mountain village
13	10-10	*CONAP* Communication Manager
14	11-10	*INAB* Project manager
15	13-10	*World Bank* Project director
16	15-10	*NGO Water for the People* Project director
17	16-10	*Water distribution* center Cobán Owner
18	18-10	Researcher: biodiversity and Mayan Q'eqchi' communities

I

Monitoring

Children monitoring survey questions
Enjoyment and Understanding: Did you enjoy reading the environmental comic? What was your favorite part?
Learning about Nature: Can you name one thing you learned from the comic about nature or the environment?
Favorite Character or Scene: Who is your favorite character in the comic, and why? Is there a scene that you liked the most? Did you feel a personal connection to any of the characters or scenes in the comic? Can you provide specific examples of scenes or characters that you found particularly engaging?
Sharing with Others: Have you talked to your friends or family about the comic? What did you tell them?
Drawing Connections: Did the comic make you think differently about trees, cloud forests, water, or taking care of the environment? How so?
Distribution Question: How did you get your copy of the comic? Was it given to you at school, in the community, kids and birds program, or somewhere else?

Teacher monitoring survey questions
Integration into Lessons: How easily were you able to incorporate the environmental comic into your teaching materials, and do you feel it complemented your existing lesson plans?
Classroom Engagement: Have you noticed an increase in students' enthusiasm or interest in environmental topics since the introduction of the comic into the curriculum?
Student Discussions: Have you observed students discussing the environmental comic among themselves? What aspects of the comic do they seem most interested in?
Knowledge and awareness: Have your students shared any specific insights or knowledge about the hydrological cycle, the importance of cloud forests and environmental issues gained from the comic?

Assesement list CCFC
Knowledge and awareness: a. Are children more aware of the challenges related to deforestation and environmental conservation as a result of reading the comic? b. Have the children in the area gained knowledge about the hydrological cycle, conservation, and the importance of cloud forests through the comic?
Community Engagement: a. Has the comic sparked discussions and activities within the local community related to environmental conservation? b. Are parents, teachers, and community leaders getting involved in educating children about conservation after the comic's introduction?
Emotional Impact: a. Has the comic influenced children's emotional connection to nature and the environment? b. Are children expressing a greater sense of responsibility and empathy toward nature and wildlife? c. The images and symbols used in the comic effectively resonate with children, making the environmental messages more memorable and impactful?