The Potential of Improved Land Management Practices to Decrease Vulnerability towards Torrential Rains as a Natural Hazard for Disasters

Case Study from the Cormier Watershed in Haiti

Master Thesis

by

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Abstract

Population pressure, deforestation and unsustainable agricultural practices have caused land degradation in the Cormier watershed in Haiti. Combined with torrential rains, hurricanes and the population's vulnerability, natural hazard triggered disaster are a challenge people in the Cormier watershed in Haiti are faced with. Even though an influence of land management on runoff is generally agreed upon, the quantification of the impact of the current land uses and the potential contribution of improved land management towards disaster risk reduction and climate change adaptation are not sufficiently established yet. Up to now, the link between changes in land use and land cover (LULC) in the Cormier watershed and the enlargement of the Cormier river in the lower zone of the watershed has not been investigated. It is unknown where exactly how much runoff is generated and which parts of the watersheds contribute the most to the runoff. Lack of monitoring systems make research on basic and detailed hydrological processes a difficult task. However, understanding the hydrological processes in the watershed as a whole is crucial for the implementation of future sustainable resource management strategies and mitigating flood and soil erosion in the region. Thus, the main purpose of this master thesis is to assess the on- and off-site impacts of the current and the potential of improved land management in the Cormier watershed in order to reduce vulnerability towards torrential rains as a natural hazard, including rainfall coming along with tropical storms and hurricanes. In a first step, current land use practices were documented for the WOCAT database on sustainable land management (SLM) and their on-site impacts on human and natural environment analysed. In a second step, the impact of the current LULC on the potential runoff was assessed with the Soil Conservation Service Runoff Curve Number (SCS-CN) model (off-site impact). In a third step, the SCS-CN model was applied to scenarios with worsened and improved LULC. The documentation of the current land use practices showed that there are alternatives to the unsustainable conventional land management (CLM). The assessed sustainable land use practices (agroforestry, vertiver terraces, Terra Preta gardens and wattle fences for gully reduction) prevent soil loss and except for vetiver terraces, they are productive for the land users. Especially agroforestry systems have a great potential in this environment. For normal rainfall events of $\leq$ 70 mm (95percentile of daily rainfall), the improved LULC scenario with agroforestry systems resulted in being the best option for reducing runoff. Even though the potential runoff increases with higher rainfall amount, areas with agroforestry produced 20% less runoff than bare soil during an extreme event like Hurricane Matthew (500mm). The south- and south-east-facing slopes were identified as hotspots of runoff contribution and of land management. On these slopes, CLM is dominant and vegetation is sparse, hence, runoff is high.

Résumé

La pression démographique, la déforestation et les pratiques agricoles non durables ont contribué à la dégradation des terres dans le bassin versant de Cormier en Haïti. En combinaison avec des pluies torrentielles, ouragans, ainsi que la vulnérabilité de la population, les catastrophes déclenchées par les aléas naturels constituent un défi auquel la population du bassin versant du Cormier est confrontée. Même si l'influence de la gestion des terres sur le ruissellement de surface est généralement acceptée, la quantification de l'impact des utilisations des terres et la contribution potentielle d'une meilleure gestion des terres à la gestion des risques et désastres et l'adaptation au changement climatique ne sont pas encore suffisamment établies. Jusqu'à présent, le lien entre les changements dans l'occupation et l'utilisation du sol dans le bassin versant et l'élargissement de la rivière Cormier dans la partie inférieure du bassin n'a pas été étudié. On ne sait pas où exactement combien d'eau de ruissellement est produite et quelles parties du bassin versant contribuent le plus au ruissellement. L'absence de systèmes de surveillance rend difficile la recherche sur les processus hydrologiques de base et détaillés. Toutefois, la compréhension des processus hydrologiques dans l'ensemble du bassin hydrographique est cruciale pour la mise en œuvre de futures stratégies de gestion durable des ressources et l'atténuation des inondations et de l'érosion dans la région. Ainsi, le but principal de ce mémoire est d'évaluer les impacts sur et hors site de l'occupation et l'utilisation du sol actuelle et du potentiel d'une meilleure gestion des terres dans le bassin versant pour réduire la vulnérabilité aux pluies torrentielles comme danger naturel, y compris les précipitations accompagnant les tempêtes tropicales et les cyclones. Dans une première étape, les pratiques actuelles d'utilisation des terres ont été documentées pour la banque de données WOCAT sur la gestion durable des terres et leur impact sur l'environnement humain et naturel a été analysé. Dans une deuxième étape, l'impact de l'occupation et l'utilisation du sol actuelle sur le ruissellement potentiel (impact hors site) a été analysée avec le modèle SCS-CN (Soil Conservation Service Runoff Curve Number). Dans une troisième étape, le modèle SCS-CN a été appliqué à des scénarios avec une gestion des terres aggravée ou améliorée. La documentation des pratiques actuelles d'utilisation des terres a montré qu'il existe des solutions alternatives à la gestion des terres non durable et conventionnelle. Les pratiques de gestion durable des terres évaluées (agroforesterie, terrasses de vétiver, jardins Terra Preta et clayonnage pour la correction des ravines) empêchent la perte de sol et, sauf pour les terrasses de vétiver, elles sont productives pour les utilisateurs des terres. Les systèmes agroforestiers ont particulièrement un grand potentiel dans cet environnement. Pour des précipitations normales de $\leq$ 70 mm (95e centile des précipitations quotidiennes), le scénario de la gestion des terres amélioré avec les systèmes agroforestiers s'est avéré la meilleure option pour réduire le ruissellement. Même si le ruissellement potentiel augmente avec la quantité de précipitations, l'agroforesterie a produit 20% moins de ruissellement que le sol nu lors d'un événement extrême comme l'ouragan Matthew (500 mm). Les pentes exposées au sud et au sud-est ont été identifiées comme des points chauds de contribution au ruissellement et de la gestion des terres. Sur ces pentes, la gestion non durable des terres est dominant et la végétation est clairsemée, donc, le ruissellement est élevé.

Preface

This master thesis would not have been possible without the support of numerous people: I would like to take this opportunity to thank the Swiss Red Cross (SRC) for the opportunity. Many thanks to Helen Gambon (former SRC Junior Program Coordinator Latin America and Caribbean) and Fabienne Weibel (SRC Programme Manager Haiti) for all the inputs and helping me organize my field trips to Haiti. Additionally, I could not have visited the Cormier watershed without the Haitian SRC staff, especially Jean Carls Dessin, Georges Jean Jaques, Déthéonom Jean-Louis, and Evale Guetchine Jean, as knowledge of the local territory and the Creole language is a necessary tool. In addition, since the transport between hotel, office and field was required, I would like to thank Jordany Petitfrère for organizing the logistics. A special thank also goes to François Dessambre and his family for hosting me in Port-au-Prince and showing me the paradise Haiti could be. Furthermore, I am much obliged to my two supervisors Prof. Dr. Chinwe Ifejika Speranza and Dr. Hanspeter Liniger: Thank you Chinwe for the enriching inputs at the beginning and at the end of my thesis. Thank you Hanspeter for the tireless support, the recommendations, the interesting discussions, and the shared experiences in Haiti. Moreover, I would like to acknowledge Jürg Krauer for the technical support, Lorenz Joss and Andrea Hürlimann for the interesting discussions on the methodology, and Tamara and Coralie for proofreading this thesis. Thank you to all Master students, with whom the lunch and coffee breaks were simply more pleasant. Thank you Igor for encouraging me to use latex and for the many hours during which you supported me technically and emotionally patiently! Finally yet importantly, I cordially thank my dear family, for the loving support you gave me during nearly three years of work.

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List of Abbreviations

AF – Agroforestry

AMC – Antecedent Soil Moisture Condition

CNIGS – Centre National de l'Information Géo-spatiale (Haitian national GIS agency)

CCA – Climate Change Adaptation

CLM – Conventional Land Management

DEM – Digital Elevation Model

DTM – Digital Terrain Model

DSM – Digital Surface Model

DRR – Disaster Risk Reduction

Eco-DRR – Ecosystem-based Disaster Risk Reduction

FAO – Food and Agriculture Organization of the United Nations

GIS – Geographic Information System

GWUE – Green Water Use Efficiency

HRU – Hydrologic Response Unit

HSG – Hydrologic Soil Group

IPCC – International Panel on Climate Change

LULC – Land Use and Land Cover

MEA – Millennium Ecosystem Assessment

NDVI – Normalized Difference Vegetation Index

NGO – Non-governmental Organization

NIR – Near-infrared

OBIA – Object-based Image Analysis

QA – WOCAT Questionnaire on SLM Approaches

QCCA – WOCAT Questionnaire on Climate Change Adaptation

QT – WOCAT Questionnaire on SLM Technologies

SCS-CN – Soil Conservation Service Curve Number

SLM – Sustainable Land Management

SRC – Swiss Red Cross

TPI – Topographic Position Indes

UNCCD – United Nations Convention to Combat Desertification

UNDRR – United Nations Office for Disaster Risk Reduction (formerly UNISDR)

UNEP – United Nations Environment Programme

UNDP – United Nations Development Programme

WOCAT – World Overview of Conservation Approaches and Technologies

Chapter 1

Introduction

1.1 Problem statement

Every year, disasters triggered by natural hazards such as droughts, floods, landslides, storms, and earthquakes occupy the front-pages of newspapers and magazines in different parts of the world. However, not all disasters make the headlines. Across the world, small-scale disasters are commonplace and are a constant threat to families and communities hidden away from the global spotlight (Harari et al. 2017). Such disasters are not just natural but a product of the social, political, economic and environmental context of the community or society in which they occur (Donovan 2017; Swiss NGO DRR Platform 2016; Cardona et al. 2012). Especially in the case of Haiti, the baseline vulnerability plays a critical role in the transition of a hazardous event to a disaster. Therefore, when using the term "natural disaster" hereafter it will always be referring to *natural hazard triggered disasters*.

Over the last few decades, the frequency and impacts of natural disasters have increased (Munich Re 2018). This cannot be explained by climate change alone: according to the International Panel on Climate Change (IPCC), unsustainable land management (e.g. deforestation in the upper zones of watersheds) as well as urbanisation and related land use may aggravate the local disaster risk (Field et al. 2012). The role of ecosystems in Disaster Risk Reduction (DRR) and Climate Chance Adaptation (CCA) has gained importance in the past few years (Harari et al. 2017; Monty et al. 2016; Doswald and Estrella 2015; Munang et al. 2013). Already in 2005, the Millennium Ecosystem Assessment (MEA) showed that many essential ecosystems are being used unsustainably, limiting their capacities to regulate the climate, provide protection with respect to hazards and sustain livelihoods (MEA 2005). This climate change, this ecosystem services will become more and more important. Small Island Developing States (SIDS), such as the Republic of Haiti, are known to be particularly vulnerable to the impacts of climate variability and change, including both extreme events and gradual environmental changes (Duvat et al. 2017; Field et al. 2014; Nelson et al. 2018). Haiti is highly exposed to natural hazards due to its geographical location. The republic is situated in the major fault line between the North American and Caribbean tectonic plates, moreover, the Caribbean is highly prone to hurricanes. It belongs to the category of countries that are recurrently affected by catastrophes and thus continuously rank among the most affected in the long-term[1] Climate Risk Index (Eckstein et al. 2019). Between 1970 and 2006, approximately six natural disasters occurred in the Caribbean annually, with Haiti and the Dominican Republic being more frequently affected (FAO 2013a). However, although these two countries share the same island (Hispaniola), they do not have the same Climate Risk Index: For the period from 1998 to 2017 Haiti ranked fourth just after Puerto Rico, Honduras and Myanmar, whereas the Dominican Republic ranked 12th (Eckstein et al. 2019). It can be assumed that one of the main causes for the difference can be found in land management. Once covered by forest, only 4% of Haiti's original forest cover remains, whereas the Dominican Republic still has an original forest area of 41% (UNEP 2013). Due to severe deforestation and fragmentation of forests, forest ecosystems have shifted to savannah and degraded grasslands (Hirota et al. 2011). Combined with poor agricultural management, intensive land use on steep slopes and a lack of soil conservation measures, Haiti is globally one of the most degraded regions in terms of soil erosion (Thummarukudy 2010; Velasco et al. 2018; UNEP 2013). This form of desertification interacts with climate change and creates even more vulnerable conditions in Haiti, such as increased drought stress (Sprenkle-Hyppolite et al. 2016; Famine Early Warning Systems Network 2015).

Historically, deforestation in Haiti was linked to agriculture and construction; today it is linked to the demand for biomass as the main energy source at household level. 3-4 million tonnes of wood (12-30 million trees) are exploited each year. This corresponds to over four times the amount of oil consumed in Haiti (Racicot 2011). Furthermore, the Haitian population has tripled in the last 60 years (World Bank 2018). These pressures on land caused severe degradation: approximately 40% of Haiti's territory is considered degraded (Bai et al. 2008). Therefore, in connection with its high precipitation regime, Haiti is particularly vulnerable to landslides, soil erosion and floods (Smucker et al. 2007). Compared to other tropical regions, the proportion of rainwater runoff is quite high in Haiti: about 45% of the amount of rainfall runs off and makes runoff water the main water cycle component (Frelat et al. 2012; Gaucherel et al. 2017). According to Gaucherel et al. (2017), this is due to Haiti's diversified and high relief. Additionally, unsustainable land management practices lead to soil degradation and increased rainfall runoff, which modifies the water balance and increases the risk of disaster (Wolfgramm et al. 2014; Sajikumar and Remya 2015; Li et al. 2018; Durán Zuazo and Rodríguez Pleguezuelo 2008). Knowing more about how improved land management could decrease vulnerability towards torrential rains as a natural hazard is relevant for Haiti regarding CCA and DRR.

1.2 State of research

1.2.1 Ecosystem services and their role in disaster risk reduction

Since the 1990s ecosystem services have become a popular scientific topic (Burkhard et al. 2010). The MEA (2005) defines ecosystem services as the benefits that people derive from ecosystems.

[1] Long-term Climate Risk index: 1998 to 2017

The protective function of ecosystems against vagaries of nature is well known by communities around the world. In the DRR community, however, ecosystems became popular only over the last decades (FAO 2013b; March 2013; Sudmeier-Rieux et al. 2006; Sudmeier-Rieux and Ash 2009; UNEP and UNISDR 2008; UNDRR 2005; Stolton et al. 2008). According to Renaud et al. (2013), the Indian Ocean tsunami in 2004 was the decisive turning point in shifting global attention to ecosystem-based approaches for disaster preparedness and risk reduction. The event drew attention to the potential role of coastal ecosystems in providing hazard protection and mitigation. Additionally, it spurred the establishment of the *Hyogo Framework for Action (2005-2015): Building the Resilience of Nations and Communities to Disasters* by the UN Office for Disaster Risk Reduction (UNDRR, former UNISDR) in 2005 (UNDRR 2005). In 2015, its successor followed: the *Sendai Framework for Disaster Risk Reduction 2015-2030: Renewing the Global Commitment to People's Resilience, Health, and Well-being* (UNDRR 2015). In both frameworks, strengthening the sustainable use and management (SLM) of ecosystems and implementing integrated environmental and natural resource management approaches are considered to be important investments in DRR. Today, the role of ecosystems in DRR is well recognised by the UNDRR. Nevertheless, Renaud et al. (2013) claim that the role of ecosystems may still be the most overlooked component in DRR and development planning because of the following reasons; Firstly, ecosystem management is rarely considered a part of the DRR solutions portfolio. In order to implement ecosystem management approaches for DRR, technical experts from the environment and the disaster management communities are required, and those usually work independently of each other. Secondly, DRR and disaster management in general are often viewed in direct competition with other development priorities. Policy-makers and decision-makers are under time pressure to demonstrate results from their efforts to protect the people against natural hazards, and ecosystem-based approaches usually take longer to implement and yield tangible outcomes in disaster risk reduction compared to engineered structures. As a third explanation, Renaud et al. (2013) highlight the poor interaction between science and policy on ecosystem-based disaster risk reduction (Eco-DRR) which has led to unclear and occasionally contradictory scientific information on the role of ecosystems for DRR. It thus remains a big challenge to scientifically quantify ecosystem services for DRR (e.g. vulnerability reduction or hazard mitigation) and to build a solid economic case for ecosystem based approaches. Hence, there is a constraint to informed decision-making on all possible cost-effective DRR options (Renaud et al. 2013).

1.2.2 Sustainable land management and land degradation

Sustainable land management is defined as the use of land resources (including soil, water, animals and vegetation) for the production of goods for human needs while ensuring the long-term productivity of these resources and improving their ecosystem services (Liniger et al. 2011; Harari et al. 2017). The health of land resources have a great impact on ecosystem services (see Fig. 3.1). According to the World Overview of Conservation Approaches and Technologies (WOCAT) land degradation is defined as "the degradation of land resources, including soils, water, vegetation, and animals" (WOCAT 2017b). They distinguish between six land degradation types: (i) soil erosion by water,

(ii) soil erosion by wind, (iii) chemical soil deterioration, (iv) physical soil deterioration, (v) biological deterioration, and (vi) water degradation; degraded ecosystems may suffer from several land degradation types simultaneously. Soil and water loss, for instance, are big issues on sloping cropland over the world (Ochoa-Cueva et al. 2015; Gessesse et al. 2015). They are natural processes which can be accelerated by human activity (Durán Zuazo and Rodríguez Pleguezuelo 2008) and lead to environmental problems reducing soil organic matter and water holding capacity, and therefore, to lower land productivity and increased runoff (Mwango et al. 2016; Tian et al. 2016; Durán Zuazo and Rodríguez Pleguezuelo 2008).

1.2.3 Runoff

(Surface) runoff is the infiltration-excess of precipitation that flows over surface. Durán Zuazo and Rodríguez Pleguezuelo (2008) review the effect of plant cover on runoff and soil erosion. They conclude that although soil erosion is more influenced by changes in precipitation and plant cover, runoff is also influenced by these factors. Moreover, they conclude that the impact of plant cover change is stronger than the impact of changes in canopy cover alone. Based on their review, Durán Zuazo and Rodríguez Pleguezuelo (2008) claim that plant cover should be considered more widely for restoring degraded environments. While Durán Zuazo and Rodríguez Pleguezuelo do not specify which plant cover it should be, Liu et al. (2018) look deeper into that area of research. They assess the impact of grass hedges planted along the contour of slope cropland on soil loss and surface runoff in China. The grass hedges (*Vetiveria ziaaniodes* (vetiver), *Amsopha fruticose* (false indigo), *Medicago sativa* (alfalfa), and *Eulaliopisi binata* (Chinese alpine rush)) were grown for 18 years and maize was planted in the alley between the hedges. Like other studies (see Mekonnen et al. 2016; Wu et al. 2010; Xiao et al. 2011), the results of Liu et al. (2018) show that grass hedges reduce both runoff and soil loss. Vetiver grass hedge treatments reduce runoff by 58%, reduce runoff speed and even collect water above the grass hedge. Sediments are deposited on and above the grass hedges and, thus, the soil thickness on and above the grass hedges increases. They conclude that among the four grasses tested, vetiver was the most effective in reducing soil loss (91.6%). They explain this by the fact that vetiver grasses have denser stems with richer and deeper roots compared to the other three grass types. In addition, in 20° slope croplands treated with vetiver hedges, the slope gradients decreased about 4°. Since soil erosion decreases with decreasing slope, the morphology of the grass hedge crop lands may became stable in the long term (Liu et al. 2018).

However, not only grass hedges are known to reduce runoff and erosion. Young (1989) and Buresh and Tian (1998), for instance, review the role of agroforestry in reducing soil degradation. Agroforestry systems are land management systems which combine elements of forestry with those of agriculture and/ or pasture. Both Young (1989) and Buresh and Tian (1998) conclude that in agroforestry systems plant litter provided by trees and shrubs hinders raindrops to dislodge soil. Moreover, runoff is slowed down due to an obstructed flow pathway and therefore the capacity to transport sediment is reduced. This coincides with Ogden et al. (2013), who compare hydrologic data of three catchments with contrasting land use and land cover: one with old-secondary forest, one with a dynamic mosaic of young forest of various ages, pasture and subsistence agriculture and one actively grazed pasture. Their results show that peak runoff rates from the pasture and mosaic catchments were 1.7 and 1.4 times those of the forest catchment, respectively. According to Ogden et al. (2013), forests reduce maximum runoff rates and totals during storms and increase the base-flow runoff in dry seasons while reducing the annual runoff due to evapotranspiration. Moreover, their results showed that the peak runoff from the old-secondary forest catchment was significantly less than that from the mosaic and pasture catchments.

1.2.4 Land use and land cover and hydrology in Haiti in general and the Cormier watershed in particular

The big Haiti earthquake in January 2010 drew global attention. About 10'000 non-governmental organizations (NGOs) were operating in Haiti after the earthquake (Edmonds 2013). The majority was based in the capital city Port-au-Prince and in Léogâne (see Fig. 1.1), a port town about 30 km west of Port-au-Prince and just 20 km south-east of the earthquake's epicentre. Several NGOs and United Nation agencies compiled information about Haiti's development and environment (see Government of Haiti 2017; UNEP 2013; USAID 2016; Swiss Red Cross 2014). For Léogâne, however, basic data on precipitation, river and spring discharge, soil erosion, rainfall runoff etc. remains sparse. Even though basic data on rainfall and river discharge would be very relevant to understand and quantify hydrologic processes in areas which are highly influenced by water, like Léogâne. The village of Léogâne sits on a delta at the intersection of three rivers, which are all prone to moderate

Figure 1.1: The study area: the Léogâne commune in pink and the Cormier watershed in blue. (The author, based on ArcGIS Online Basemap *World Imagery*)

and high flood risk. This is shown by the hazard map, published by the government of Haiti in 2016 (see Fig. 1.2). It can be assumed, that poor land management in these three watersheds enhances the flood risk and hence the vulnerability to torrential rains as a natural hazard, but no baseline data exists to solidify this assumption.

As mentioned above, Haiti has been severely deforested and suffers now from land degradation. In previous years, many studies on land use and land cover (LULC) mapping and LULC change based on satellite data have been conducted in Haiti. Most of them assessed the forest cover in Haiti on national level. Churches et al. (2014), for instance, did a supervised classification using a Landsat 5 imagery in order to estimate total forested area in Haiti. They used the Food and Agricultural Organisation (FAO) land cover classification system. Their study showed that 30% of Haiti is covered by forest. Other studies assessed far less forest: <1% (Erikson 2004; Huber et al. 2010; Williams 2011) or 5% (Higuera-Gundy et al. 1999). Churches et al. explain that these differences may be attributed to the fragmented and patchy nature of Haiti's forests and to the spatial resolution of satellite images used to estimate the forest cover. The coarser the spatial resolution, the more mixed pixels contain small patches of forest and shrub cover. With a higher resolution, small forest patches are distinguished from shrub cover pixels and can be recognized as individual forest pixels (Churches et al. 2014). Another explanation may be the definition of "remaining" forest cover. In some studies they refer to the remaining *original* forest cover, which explains the low values, in others they refer to natural and reforested forest areas, as in Churches et al. (2014). For the region of Léogâne, there are some land use maps available, but they usually focus on the town of Léogâne and

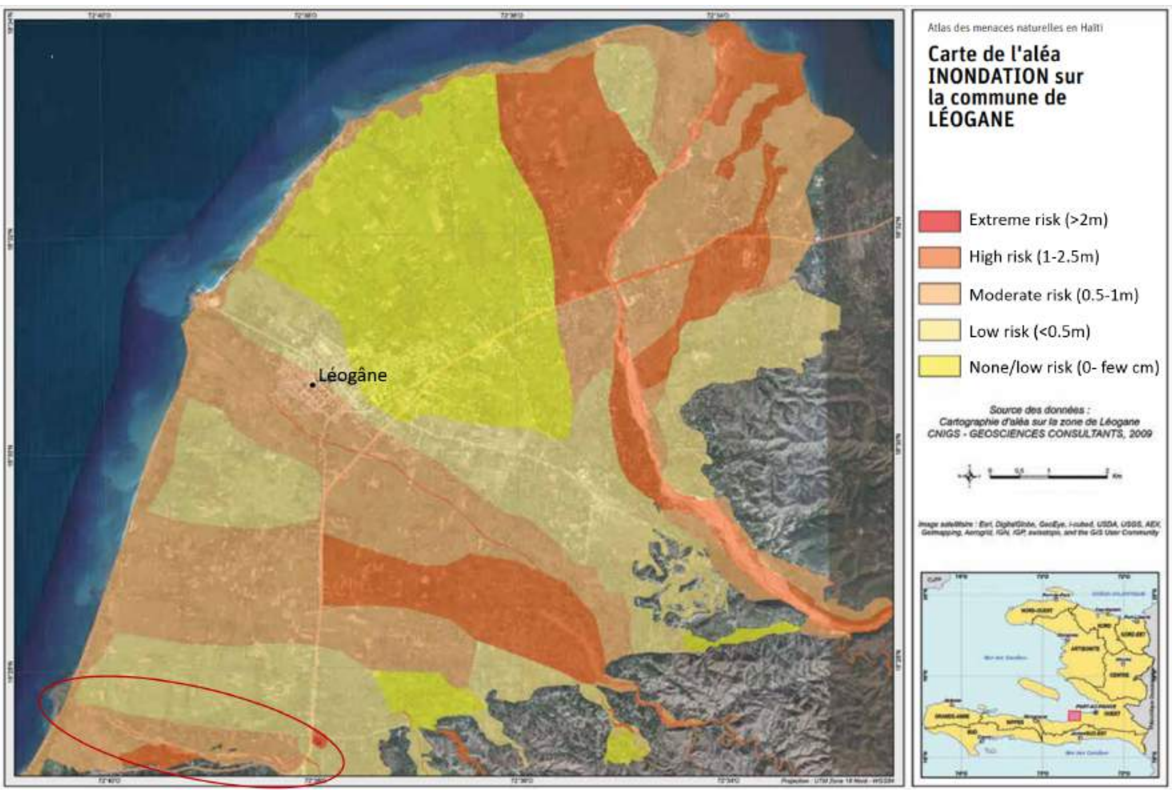

Figure 1.2: Flood risk map of the Léogâne Delta, all three rivers (Cormier river showed in the red circle) are prone to moderate and high flood risk. (adapted CIAT 2016)

the delta. The Cormier watershed (see Fig. 1.1) is roughly classified as *zone of natural environment* (JICA 2011) or *moderate dense agricultural zone* (CNIGS et al. 2012).

The Cormier watershed is understudied. At the time of this study, there were no discharge data available for the Cormier river. During the dry season, the Cormier river is a tickle of water and at some points only 10cm deep. This enables people to use the riverbed as an additional road. However, according to people living in the area, the discharge increases rapidly whenever it rains. When exploring the study area in Google Earth and Google Engine time-lapse (Fig. 1.3), one can see that in less than 20 years the riverbed has broadened significantly and formed a delta, which is now about 250m long. Moreover, people living in the area claim that the Cormier watershed is much less vegetated today compared to how it used to be during their childhood. Among others, this might be caused by due to the conventional land management (CLM) practice, which is locally called "culture sarclée" (fren. for *weeded/ ploughed crop*). Due to the steep topography, the population pressure, the lack of agrochemicals and the missing access to mechanization, land users are forced to cultivate land on steep slopes and plough the soil by hand. First, they loosen the soil with the hoe or pickaxe and in a second step, they do ridges or terraces (depending on the slope) following the contour lines. After ploughing and after the harvest, the soil is loose and has no vegetation cover; hence, is very vulnerable to erosion, especially by water. Therefore, this local CLM can be considered unsustainable.

Figure 1.3: Changes in Cormier's riverbed. (Google Earth 22.06.2002, 6.02.2018)

1.3 Research gap, objectives and research questions

Even though an influence of land management on the surface runoff is generally agreed upon, the quantification of the impact of the current land uses and the potential contribution of improved land management towards DRR and CCA is not sufficiently established yet. Up to now, the link between changes in land use and land cover in the Cormier watershed and the enlargement of the Cormier riverbed in the lower zone has not been investigated. It is still unknown where exactly how much runoff is generated and which parts of the watersheds contribute the most to the runoff. Lack of monitoring systems makes research on basic and detailed hydrological processes a difficult task. However, understanding the hydrological processes in the watershed as a whole is crucial for the implementation of future sustainable resource management strategies and mitigating flood and erosion in the Cormier region.

Thus, the main purpose of this master thesis is to assess the impact of the current and the potential of improved land management in the Cormier watershed to reduce vulnerability towards torrential rains as a natural hazard for disaster, including rainfall coming along with tropical storms and hurricanes. Hence, the main research question is:

What are the opportunities and potentials of improved land management practices to mitigate the impacts of climate change and to decrease vulnerability towards torrential rains and floods?

The following objectives and sub-questions are formulated:

Objective 1) Identification of relevant current conventional and sustainable land management practices and their on-site impacts including the runoff they produce: The first objective aims to identify different land use practices within the study area and compare their on-site impacts on natural and human environment. The following research question is pursued:

Q1 What on-site impacts on human and natural environment do the sustainable land management (SLM) technologies have compared to the conventional land management (CLM) technology?

Objective 2) Assessment of the off-site impacts of current land management practices within the watershed: The second objective aims to understand and quantify the hydrologic processes within the Cormier watershed. The research question for this objective is:

Q2 How does the current land use and land cover contribute to the total runoff of the watershed?

Objective 3) Identification of different scenarios of land management change and their potential to reduce or increase runoff: The third objective follows up on the second one and assesses the potential of worsened and improved land management to increase or reduce runoff (flood flows). The following research question is formulated:

Q3 How do the worsened or improved land management contribute to the total runoff of the watershed?

1.4 Research challenges and limitations

Researchers in remote areas like the mountainous region in southern Léogâne face several challenges. Probably the biggest challenge is the data scarcity. In the Cormier watershed there are no hydrological monitoring stations and there is no discharge data available for the river. It is therefore not possible to compare the results of this thesis (potential runoff modelled with the Soil Conservation Service Curve Number (SCS-CN)) and the actual river discharge. Furthermore, there are no weather stations in the area. The location and quantity of rainfall in the area is unknown. To overcome this challenge rainfall data from other regions with similar climate can be used to approximate realistic rainfall scenarios that allow to model potentials rather than absolute values. Therefore, this thesis can only make meaningful statements about the potential surface runoff contribution of different land uses and based on this identify potential hotspot areas. In this regard, this thesis aims to help to better manage land resources and thereby decreasing vulnerability towards natural hazards by creating a better understanding of ecosystem-based disaster risk reduction and climate change adaptation in data scarce areas.

Chapter 2

Study Area

The Republic of Haiti is located on the island of Hispaniola in the Greater Antilles archipelago of the Caribbean Sea. It occupies the western third (27,750km^2) of the island. The two thirds in the east belong to the Dominican Republic. About 30km west of Port-au-Prince, the capital of Haiti, is Léogâne, which is located in the eponymous coastal commune as illustrated in Figure 1.1. Léogâne was the closest town to the epicentre of the 2010 earthquake and was catastrophically affected. The Swiss Red Cross (SRC) has been active in this region ever since. Today, the SRC has projects in five southern communal sections of Léogâne[1]: Palmiste à Vin, Fonds de Boudin, Cormier, Petit Harpon and Fond d'Oie. The Cormier watershed analysed in this thesis is located to a large extent in the communal section Cormier (Fig. 1.1). The catchment area is about 30.4km^2. In the following, human and natural environment of Haiti will be presented with focus on Léogâne.

2.1 Human environment

Haiti's vulnerability to natural hazards is not only due to its geographic location. It is also due to its socio-ecological sensibility (Weissenberger 2018). Haiti is considered to be the poorest country of the western hemisphere. Its Human Development Index for 2017 was 0.498, which gives it a rank of 168th out of 189 countries and territories (UNDP 2018). Furthermore, the population density is increasing rapidly and has almost tripled in the past 60 years: from 3.8 million inhabitants in 1960 to 10.9 million people in 2017 (World Bank 2018).

In rural Haiti, agriculture remains the primary income-generating activity: 70% of the Haitian population depends on it and it contributes to 25% of the gross domestic product (Bargout and Raizada 2013; Dolisca et al. 2009; Singh and Cohen 2014). With increasing population density, the pressure on arable land has been increasing at the expense of forests (Velasco et al. 2018) and the unorganized land use rights and untitled land owner ship do not provide incentives for reforestation (Dolisca 2005).

[1] Unless specified in the text, "Léogâne" refers to the commune, not to the arrondissement or town.

2.2 Natural environment

2.2.1 Climate

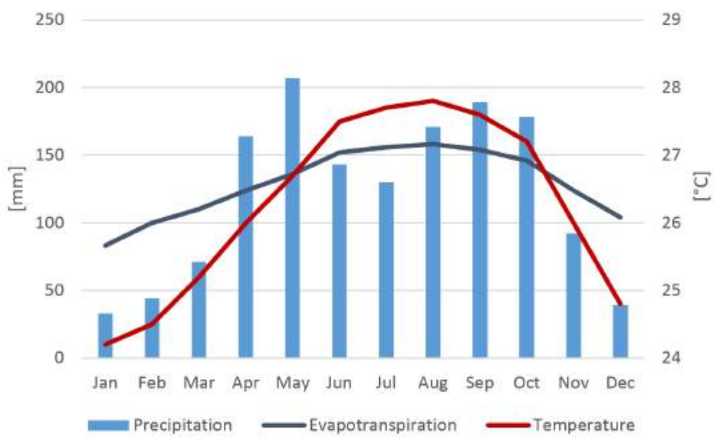

Figure 2.1: Climate of Léogâne. (The author, based on data of FAO (2000, In: Joseph (2006)))

The dominant wind system affecting Haiti is the humid trade wind coming from the north-east (Wilson et al. 2001). Combined with the orientation of the mountain ranges, a rain shadow effect can be observed on the south facing slopes of major mountain ranges (Wilson et al. 2001), where leeward slopes receive up to three times less rainfall than windward slops (World Bank 2011). A large portion of rainfall in Haiti results from convective systems, which are highly variable over time and space. This causes very intensive rainfall events with high kinetic energy and hence, results in high rainfall erosivity (Prince et al. 2002). Official climate data is hardly available for the region of Léogâne and in literature, different mean annual rainfall amounts are given: 1154mm (Woodring et al. 1924), 1347mm (Climate-Data.org n.d.), and 1461mm (FAO 2000, In: Joseph (2006)) and 1490mm/yr (Gaucherel et al. 2017). For his study, Joseph (2006) used precipitation, evapotranspiration and temperature data from the FAO (2000). This FAO climate data was inaccessible at the time of the present master thesis and only available in the annex of Joseph's Master thesis (Joseph 2006). Figure 2.1, which was derived from this data, illustrates the tropic climate with dry winter (November-March) and two pronounced rainy seasons (April/Mai and August-October). Between the two rainy seasons there is a two month period with less rainfall (June-July). The annual temperature is 26.3°C and the annual evapotranspiration is 1547mm (FAO 2000, In: Joseph (2006)). It can be assumed that the mountainous areas, called the *Mornes*, are considerably cooler and more humid (Higuera-Gundy et al. 1999; MARNDR 2012).

Concerning climate change, the annual temperature in Haiti is expected to increase by 0.8 to 1°C by 2030 and 1.5 to 1.7°C by 2060 and precipitation is expected to decrease by 5.9 to 20% by 2030 and 10.6 to 35.8% by 2060 (Ministère de l'Envionnement 2006). Moreover, it is predicted that the rainy days will decrease as well and seasonal rains will become more variable (Ministère de l'Envionnement 2006). Furthermore, it is presumed that strong hurricanes will increase in frequency (Trenberth et al. 2007; Goldenberg et al. 2001) and that there will be more extreme events like droughts and floods in the future.

2.2.2 Vegetation

Haiti is well known for its severe deforestation. About 100 years ago, Woodring et al. (1924) already observed that although being a tropical country, Haiti only had few areas "where the vegetation presents the aspect of an impenetrable tropical rainforest, the aspect that is so commonly visualized by one thinking of a tropical region" (Woodring et al. 1924, p. 57). As mentioned in Chapter 1.2.4, the percentage of remaining forest cover in Haiti cited by recent scientific publications varies widely: from <1% (Erikson 2004; Huber et al. 2010; Williams 2011) to 5% (Higuera-Gundy et al. 1999). The total forest cover (natural and reforested) is about 30% (Churches et al. 2014). The severe deforestation in Haiti is often demonstrate with an aerial image of the border to the Dominican Republic (see Fig. 2.2)

Tropical dry forests occupy coastal lowlands on the southern peninsula and the Mornes support mesic plant communities and pine forests (Higuera-Gundy et al. 1999). As explained in Chapter 2.2.1, north-east slopes of major mountain ranges receive more moisture and are therefore more heavily wooded than the drier south-west slopes. Having a close look on Google Earth, one can observe this characteristic vegetation pattern in the Mornes of Léogâne (Fig. 2.3). However, in this region it is rather a north-west/south-east aspect. This could be explained by the orientation of the mountains as well as the solar radiation. The latter was also observed in Papua New Guinea by Smith (1977): Unlike in temperate zones, where insolation is higher on equator facing slopes than on poleward ones, in the tropics, slopes of different aspect are not expected to differ in the insolation they receive. However, due to clear mornings and cloudy afternoons, the east facing slopes experience higher amounts of insolation. Greater insolation and resulting higher maximum temperatures lead to greater evaporation and hence to drier microclimates on east facing slopes (Smith 1977). In the local context of Léogâne, land users are aware of the higher insolation and dryer conditions and therefore plant crops that like these conditions (e.g. peanuts) on the south-east facing slopes while agroforestry systems are maintained on the cooler and more humid north-west facing slopes.

Figure 2.2: Aerial Image of the border between the Haitian and the Dominican Republic. (UNEP 2011)

Figure 2.3: Differences in vegetation between north-west and south-east facing slopes. (Google Earth 06.02.2018)

2.2.3 Topography, geology and soils

Haiti's predominately rugged topography is reflected in the countries indigenous Taíno-Arawak place name *Ayti*, which means "Mountainous Land" (Hadden and Minson 2010). 65% of its territory has slopes exceeding 40%, uplands represent 15%, and plains occupy 20% (World Bank 2012). Léogâne is characterized by its big fan delta as well as the rugged landscape with steep mountain chains and deep valleys.

The geology map provided by the Haitian government (Lambert et al. 1987) is from 1987. As already mentioned, the epicentre of the earthquake of 2010 was near the town Léogâne and therefore, many studies were published on the regional geology of Léogâne. Nevertheless, no newer geology map is available. As can be seen in Figure 2.4, basaltic bedrock (shown in blue color *Cb, Ca*) is clearly dominant in the Mornes, including the Cormier watershed. These massive rocks are from the Cretaceous formation and sometimes have weak cohesion at the surface. Therefore they may be prone to erosion (Lentini and Di Crecco 04.2012). The soils formed by this basaltic rocks are usually clay-rich and contain high amounts of oxides and hydroxides of iron and manganese (Lentini and Di Crecco 04.2012). However, there are no detailed soil maps for the region of Léogâne. According to the Soil Atlas of Latin America and the Caribbean (Gardi et al. 2014), the following assumptions can be made for the soils in the study area: The Léogâne delta, as other coastal plains in the Caribbean, has deep, clay-rich and often calcareous alluvial soils (e.g. Vertisols and Luvisols). Under tropical forests, there are usually Ferralsols. This classical reddish or yellowish toned soil of the humid tropics has a thick texture and is usually heavily leached due to the intense weathering (Gardi et al. 2014). They have good water conductivity and a high infiltration rate (Zech et al. 2014). In mountainous areas, surface soils are often exposed to erosion, which leads to weakly developed Cambisols (Gardi et al. 2014). Most Cambisols are loamy (medium-texture) and they usually have a high porosity, good

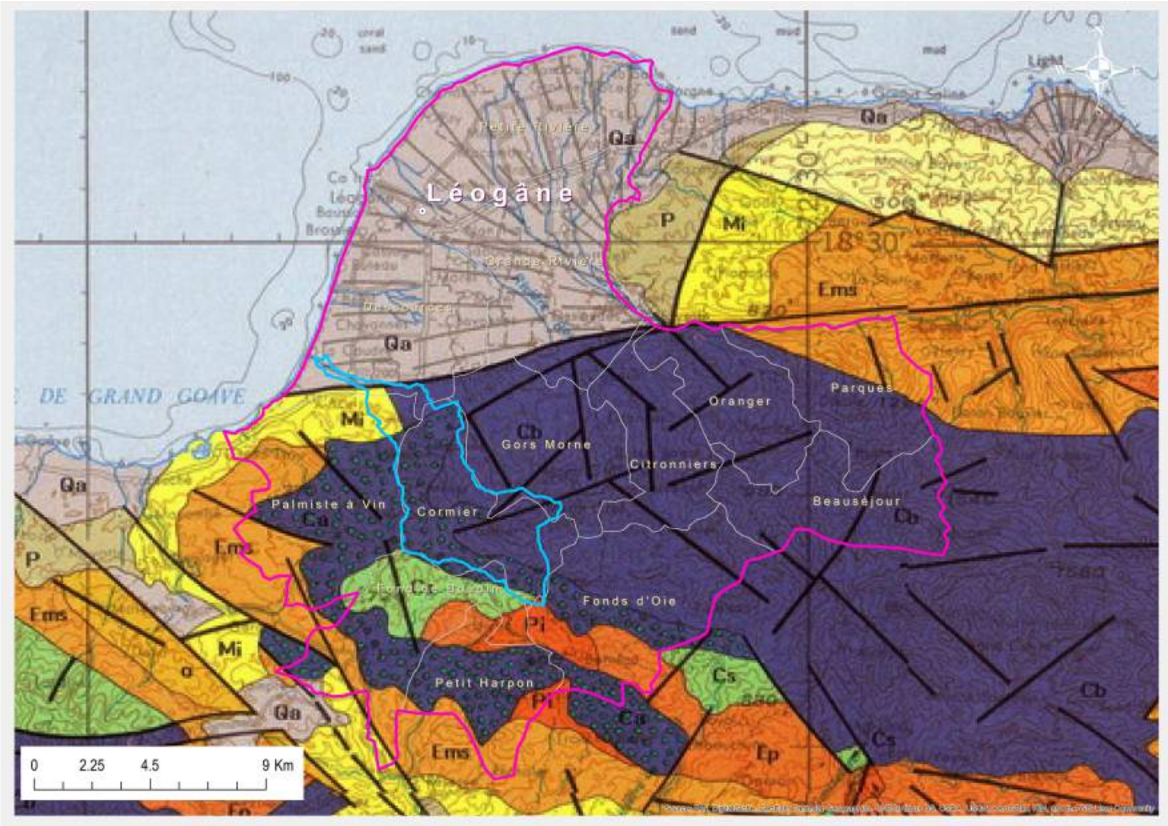

Figure 2.4: Geology map of Haiti with the commune of Léogâne in pink and the Cormier watershed in blue colour. Over 90% are part of a basalt formation (purple). (Lambert et al. 1987, adapted) (see Apenndix. A.1 for detailed legend)

water holding capacity and good internal drainage (Driessen et al. 2000).

Chapter 3

Conceptual Framework and Relevant Definitions

The present master thesis deals with the impact of land management practices to increase resilience towards torrential rains as a natural hazard. This chapter explains the associated theoretical and methodological concepts and approaches.

3.1 Disaster Risk Reduction and Climate Change Adaptation

Both Disaster Risk Reduction (DRR) and Climate Change Adaptation (CCA) are policy goals to reduce vulnerability and enhance resilience (Begum et al. 2014). Whereas DRR is concerned with an ongoing problem (disaster) CCA is concerned with an emerging issue (climate change). In the following, both concepts will be presented separately and then linkages between them will be shown.

Disaster Risk Reduction
A hazard is a process, phenomenon or human activity that may cause social and economic disruption, property damage, loss of life, injury or other health impacts, or environmental degradation (UNDRR 2017). The origin of a hazard may be natural, anthropogenic or socio-natural: **Natural hazards** are associated with natural phenomena such as extreme rainfall, volcanic eruption, earthquakes, dry spells or storms; **Anthropogenic hazards** are human-induced hazards which are induced entirely or predominantly by human activities and choices like pollution or technological accidents; **Socio-natural hazards** are associated with a combination of natural and anthropogenic factors, such as climate change or environmental degradation. (UNDRR 2017; Harari et al. 2017). When a hazard coincides with people or assets that are exposed and vulnerable to that hazard and lack the capacity to deal with the impacts, the hazard turns into a **disaster** (Harari et al. 2017). A disaster refers to a serious disruption of the functioning of a community or a society due to a hazardous event, causing human, material, economic, and environmental losses and impacts (UNDRR 2017).

Based on the terminology of the UN Office for Disaster Risk Reduction (UNDRR, formerly UNISDR), **disaster risk** is determined probabilistically by the function of hazard, exposure, vulnerability and capacity (UNDRR 2017; Harari et al. 2017):

$$DisasterRisk = \frac{Hazard \times Exposure \times Vulnerability}{Capacity} \tag{3.1}$$

Hazard, the first factor of the risk equation, varies by its intensity, frequency and probability. The second factor is **exposure**, which describes “the situation of people, infrastructure, housing, production capacities and other tangible human assets located in the hazard prone zone” (UNDRR 2017, 18). The third one is **vulnerability**, meaning the “conditions determined by physical, social, economic and environmental factors or processes which increase the susceptibility of an individual, a community, assets or systems to the impacts of hazards” (UNDRR 2017, 14). These three factors are multiplied and then divided by the **capacity**, “the combination of all strengths, attributes and resources available within [...] [a] community or society to reduce and manage disaster risk and strengthen resilience”[1] (eg. institutions, human knowledge or infrastructure) (UNDRR 2017, 12). According to Equation 3.1, the risk of natural hazard triggered disasters can be reduced, if either one factor of the numerator (hazard, exposure or vulnerability) is reduced or the denominator (capacity) is enhanced.

Following from the definitions above, **DRR** aims at contributing to strengthening resilience (see Definition in Chap. 3.3.1) and to achieving sustainable development by avoiding (preventing) or limiting (mitigating or adapting to) the adverse impacts of hazards. However, DRR also includes the preparedness and response programme for reducing disaster risk (UNDRR 2009a; Begum et al. 2014).

Climate Change Adaptation (CCA)

Due to changes in climate in recent decades there have been impacts on both natural and human systems all over the world (Field et al. 2014). Adapting to negative impacts of climate change is crucial to reduce the vulnerability of society to variability and changes in the climate system (Begum et al. 2014; Sarkar et al. 2012). CCA is understood as the "adjustment of natural or human systems in response to actual or expected climatic stimuli or their effects, which moderates harm or exploits beneficial opportunities" (UNDRR 2009b, p. 3). However, according to Begum et al. (2014), CCA does not result from one single action. Multiple actions with the involvement of multiple stakeholders are needed to alter exposure, reduce sensitivity of the land use system to climate change impacts, and to increase the adaptive capacity of the system. The CCA strategies have to be target-oriented in order to reduce the vulnerability and increase the adaptive capacity of poor people affected by climate stress as well as to contribute to poverty alleviation (Begum et al. 2014).

Linking DRR and CCA

Many natural hazards (e.g. storms, droughts or floods) are influenced by climate change in their frequency, intensity, spatial extent, duration, and timing (Harari et al. 2017; Field et al. 2012). Therefore, DRR and CCA overlap to a large extent although DRR also focuses on non-climate-related disasters, and CCA additionally addresses the effects of gradual climate changes and related long-term

[1] Resilience is defined as “the ability of a system, community or society exposed to hazards to resist, absorb, accommodate, adapt to, transform and recover from the effects of a hazard in a timely and efficient manner, including through the preservation and restoration of its essential basic structures and functions” (UNDRR 2017, 22).

adjustments required to deal with this changes. Both CCA and DRR are concerned with vulnerability reduction and enhancing resilience, and share a common conceptual understanding of risk and how to decrease people's vulnerability and exposure to these. Hence, a combined approach is useful in both development planning and decision-making at national, regional and global level (Begum et al. 2014; Harari et al. 2017).

3.2 Sustainable land management and ecosystem-based DRR and CCA

Ecosystem-based Disaster Risk Reduction (Eco-DRR) and Ecosystem-based (Climate Change) Adaptation (EbA) "apply ecosystem-based solutions, such as the conservation, restoration and the sustainable use and management of land, wetlands and other natural resources, in disaster and climate risk management" (PEDRR 2016, p. 2). Regarding the disaster risk Equation (3.1), well-managed and healthy ecosystems can change three aspects. First, they **prevent hazards or mitigate the impacts** (e.g. vegetation cover and root structures on slopes may prevent landslides by binding soil together and, therefore, increasing slope stability and protecting against erosion (Peduzzi 2010; Papathoma-Koehle and Glade 2013; Jaquet et al. 2013)). Second, they **control exposure** of people and their productive assets to hazards (e.g. vegetation litter, shadow crops and nutrient-enriching plant conserve soil and retain moisture, hence, they increase resilience to drought (Renaud et al. 2013)). Third, ecosystems **reduce vulnerability** to disasters by providing basic needs (e.g. food, shelter and water, and sustaining human livelihoods - before, during and after hazard events (Ingram et al. 2012; Peduzzi et al. 2013; Mavrogenis and Kelman 2013)).

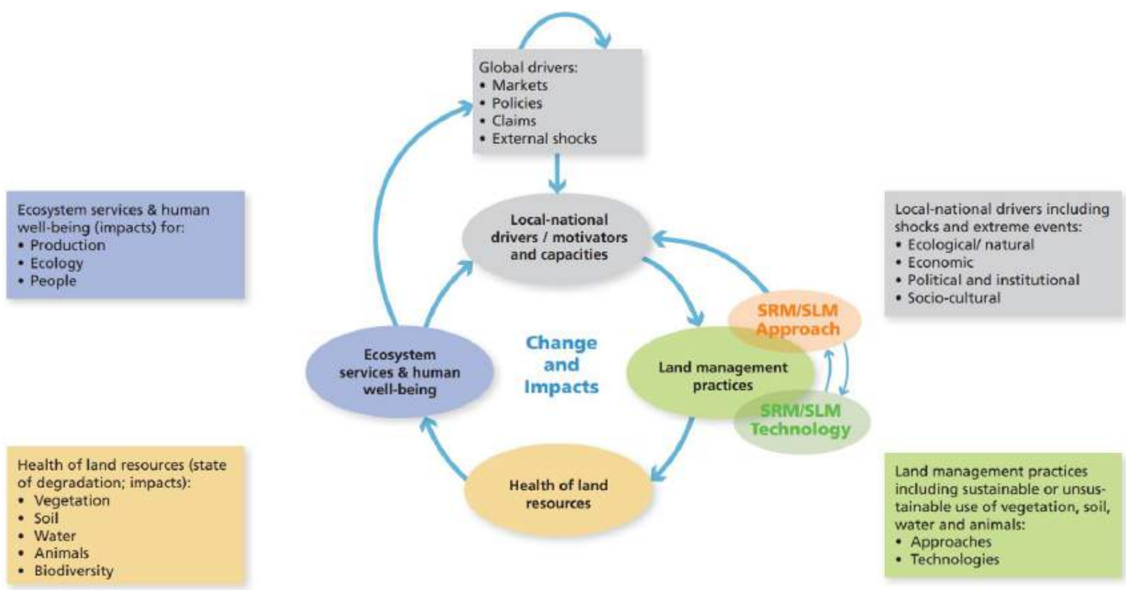

Figure 3.1: Drivers-Practices-Health/State-Ecosystem Services (Liniger and Mekdaschi Studer 2019, p. 57). This framework was originally developed for sustainable rangeland management (SRM), however, it can be used for different kinds of land management practices.

However, "unsustainable land use is driving degradation - long-term loss of ecosystem function and productivity from which the ecosystem cannot recover unaided, and which requires greater and greater external inputs to repair" (Bai et al. 2013, p. 359). In 2005, an estimated 60% of the ecosystem services assessed were used unsustainably or being degraded (MEA 2005). The rangeland management framework proposed by Liniger and Mekdaschi Studer (2019), illustrates how land management practices (sustainable and unsustainable) impact the health (state) of land resources and those, in turn, impact the ecosystem services. Sustainable land management (SLM) is defined as the use of land resources (including soil, water, animals and vegetation) for the production of goods for human needs while ensuring the long-term productivity of these resources and improving their ecosystem services (Liniger et al. 2011; Harari et al. 2017). A SLM practice can be a *technology* as well as an *approach* (Harari et al. 2017). SLM technologies refer to physical practices, which control land degradation and/or enhance productivity. One technology can consist of one or several measures. SLM approaches are ways and means used to implement SLM technologies. This may include among others technical and material support and stakeholder engagement. With the rangeland management framework the interdependences of land use in Haiti and its impacts on rainfall runoff can be better understood:

External (global, national or local) drivers influence land management practices in Haiti. These drivers can be socio-economic or natural. The market, for instance, is a socio-economic diver. The demand for peanuts, which need sun and dry climate, leads land users to deforest the sunnier and drier south-east facing slopes. Policies are socio-economic drivers. In Haiti, for instance, the land tenure situation does not provide incentives for reforestation (Dolisca 2005). Natural drivers are the rugged topographic conditions, climate change and natural hazards (external shocks). The land management practices impact natural resources. Unsustainable land use has a negative impact on health of land resources; it may, for example, cause soil erosion and lead to soil degradation and reduced vegetation cover. This, in turn, impacts ecosystem services and hinders them to reduce disaster risk. For instance, reduced vegetation cover increases soil loss and rainfall runoff. With SLM technologies and approaches, however, the health of land resources can be improved, ecosystem services can be strengthened and vulnerability towards torrential rains can be reduced[2].

3.3 Other theoretical and methodological concepts and approaches

3.3.1 Resilience

The concept of resilience has been used in natural sciences, and in particular in ecology, for over 40 years (Holling 1973). Nevertheless, its definition and application remains confusing. In this thesis, resilience is used according to UNDRR terminology. The (UNDRR 2017, p. 22) defines resilience as "the ability of a system, community or society exposed to hazards to resist, absorb, accommodate, adapt to, transform and recover from the effects of a hazard in a timely and efficient manner, including through the preservation and restoration of its essential basic structures and functions through risk management".

[2] In this master thesis it is not only the vulnerability of people, but also the vulnerability of land that is given attention to.

3.3.2 Land use and land cover

Studies concerning land resources usually assess land use and land cover (LULC). For this thesis land cover and land use are defined according to Comber et al. (2008). Land cover refers to the physical material we see at the surface of the earth. It includes trees, grass, bare ground, water, asphalt etc. In terms of remote sensing it "is the material which we see and which directly interacts with electromagnetic radiation and causes the level of reflected energy which determines the tone or the digital number at a location in an aerial photograph or satellite image" (Comber et al. 2008, p. 4). Land use is a socio-economic activity and describes how humans exploit the land cover. Commonly recognised classes of land use are urban and agricultural land uses. (Comber et al. 2008)

3.3.3 Land degradation neutrality

With the Sustainable Development Goal (SDG) 15.3 (part of SDG 15, Life on Land), the United Nations Convention to Combat Desertification (UNCCD) aims to achieve a land degradation-neutral world by 2030. Land degradation neutrality is defined as "a state whereby the amount and quality of land resources necessary to support ecosystem functions and services and enhance food security remain stable or increase with specified temporal and spatial scales and ecosystems" (Orr et al. 2017, p. 8). The three land degradation neutrality indicators are: i) land cover, ii) land productivity, and iii) carbon stocks. WOCAT, the global network of SLM specialists dedicated to combating land degradation, promotes the scaling out of SLM, hence, contributes to land degradation neutrality (Liniger et al. 2019; van Haren et al. 2019; Gonzalez-Roglich et al. 2019; García et al. 2019; Riva et al. 2017).

3.3.4 Object-based Image analysis

There are two types of LULC mapping based on satellite images; pixel-based image analysis and object-based image analysis. First-mentioned, analyses the spectral properties of each single pixel without considering its contextual or spatial information. Comparing to earlier satellites, the spatial resolution of remote sensing imagery has improved considerably in the 21st century. Today, remote sensing images may have a resolution of $\leq$ 1 x 1 m and, therefore, pixels are often smaller than the average size of the object in focus. For the pixel-based classification algorithms it has become challenging to extract the desired information from such high resolution data. More and more, the so-called "salt and pepper" effect is observed (see Fig. 3.2): pixel-based methods often suffer from high levels of noise (image blurs and inaccuracies) in the classification when applied to high resolution images. This leads to overall inaccuracies and hampers the evaluation. Starting from this problem, the need for considering spectral and spatial properties of the surrounding pixels emerged. Recent computer softwares have therefore completed a paradigm shift to object-based image analysis (OBIA). (Weih and Riggan 2010; Jensen 2015; Huerlimann 2019)

Figure 3.2: The "salt-and-pepper" effect occurs when pixel-based methods are applied to high resolution images and the resulting classification show restless structures in form of speckles or illogical pixel values (left). This leads to inaccuracies and hampers the evaluation. The object-based method (right), however, first segments the image into image-objects and then classifies the objects based on their spectral and spatial attributes. (Kelly and Kersten 2011)

Principles of GEOBIA

Hay and Castilla (2008, p. 77) define Geographic Object-Based Image Analysis (GEOBIA) as "a sub-discipline of *Geographic Information Science (GIScience)* devoted to developing automated methods to partition remote sensing imagery into meaningful image-objects, and assessing their characteristics through spatial, spectral and temporal scales, so as to generate new geographic information in GIS-ready format". This definition emphasises the two fundamental work processes of OBIA: the image segmentation and the classification of the segments (see Fig. 3.3). First, the satellite image is segmented into image-objects (group of spatially connected pixels with similar spectral properties). These image-objects consist of pixels with similar spectral and spatial properties. Subsequently, in a second step, the demarcated image-objects are classified to "real world" objects. The classification is done based on the image-objects' spectral properties, shape, spatial context or texture. (Myint et al. 2011). It is the emphasis and dependency on remote sensing and geographic information that distinguishes GEOBIA from general OBIA, which is used in related disciplines such as Computer Vision and Biomedical Imaging. In conclusion, GEOBIA generates geographic information system (GIS) ready outputs based on remote sensing data and represents a critical bridge between the raster domain of remote sensing and the vector domain of GIS. (Hay and Castilla 2008)

Strengths and weaknesses of OBIA and GEOBIA

According to Hay and Castilla (2008, p. 83), one of the biggest strengths of GEOBIA is image segmentation, which is similar "to the way human conceptually organize the landscape to comprehend it". Other strengths are that image-objects have features such as shape, texture, and contextual relations with other objects, which individual pixels lack and that image-objects are easier to be integrated into a vector GIS than raster maps classified based on pixels (Hay and Castilla 2008). For Blaschke (2010), the central strength is the segmentation on different levels. For example, at coarser levels, fields or forest stands can be distinguished, while at finer levels, it can be diversified between individual trees or plants. Moreover, the use of image-objects generally leads to a higher computing speed due to the smaller number of base units (Jensen 2015). Nevertheless, Hay and Castilla (2008) and Blaschke (2010) agree that processing large datasets remains a big challenge.

In addition, the higher resolution of the image data also brings other new difficulties, such as the now emerging heterogeneity of vegetation or shadow effects.

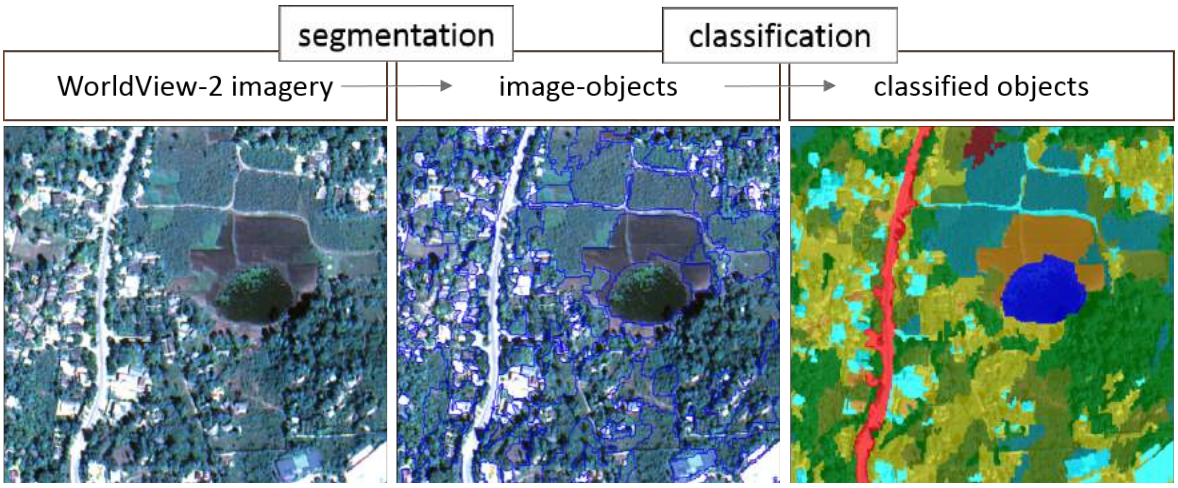

Figure 3.3: Process steps for object-based image analysis (OBIA). (Huerlimann 2019, adapted)

Chapter 4

Material and Methods

In this chapter the methods applied for each research sub-question are presented. First, the methods used to compare the conventional and sustainable land management practices are explained, including the selection of the land management practices (4.1.1), some details on the field trip (4.1.2), short presentation of the WOCAT Questionnaires (4.1.3), and the analysis of those aforementioned questionnaires (4.1.4). In a second part, the methodological approach of assessing the land use impacts within a watershed is shown. This is done by shortly presenting the used data (4.2.1)and softwares (4.2.2), followed by an explanation of the methodology of the land use and land cover mapping (4.2.3) and runoff calculation (4.2.4).

4.1 Comparing on-site impacts of sustainable and conventional land management practices

The first research question is aimed at gathering knowledge about the processes of the human and environment relationships by identifying different land use practices within the study area and comparing them.

4.1.1 Identifying different land management practices within the SRC project area

To compare the impacts of the land management practices, five different land management technologies applied in the SRC Project area in Léogâne were selected. The selection was made on the basis of the following criteria; First, to be able to compare sustainable and unsustainable land management, both had to be present in the examples. Second, to improve the comparability, the assessed technologies should be practised under the same conditions (e.g. climate, topography, exposure to natural hazards). Third, only technologies belonging either to the category of Eco-DRR or to bioengineering measures for flood reduction were used as examples for SLM. These criteria were defined in discussions with experts for sustainable land management and the local context of Léogâne. The experts were Helen Gambon (former SRC Junior Program Coordinator Latin America and Caribbean), Fabienne Weibel (SRC Programme Manager Haiti) and Hanspeter Liniger (Research Associate at the Centre of Environment and Development University of Bern with focus on sustainable land management). Eventually, the following five technologies were selected:

- Agroforestry systems
- Conventional land management (CLM)[1]
- Progressive bench terraces formed by vetiver stripes and trees
- Wattle fences for gully correction
- Terra Preta raised garden beds

Agroforestry systems and the CLM represent the traditional land management practices in Haiti; they have been practised for over 50 years. The vetiver terraces, wattle fences, and Terra Preta gardens are SLM technologies promoted by the SRC.

4.1.2 Data collection during the field trip in autumn 2017

The field trip to the SRC project area in the Mornes of Léogâne took place in autumn 2017. For organizational and logistic reasons the stay had to be split up in two three-week blocks: one from the 24th of September to the 15th of October and second one from the 4th to the 27th of November. During these six weeks the author familiarised with the different land use practices within the study area. The break between these two blocks was used for processing the collected data, e.g. for entering the information collected with the questionnaires into the WOCAT database. An important resource person was Jean Calrs Dessin, the SLM project leader of the Haitian SRC-staff; especially when filling out the WOCAT Questionnaires on SLM Technologies (QT) (WOCAT 2017b) and Climate Change Adaptation (QCCA) (WOCAT 2017a).

4.1.3 WOCAT and the questionnaires on SLM technologies and climate change adaptation

The World Overview of Conservation Approaches and Technologies (WOCAT) is a global Network that emerged in the early 1990s. The network was built by soil and water conservation specialists from all over the world with "the conviction that more was being done to care for land than general received wisdom on land degradation would suggest" (Schwilch et al. 2014, p. 984). In 2014, WOCAT was officially recognized by the UNCCD as the main recommended global SLM database for best practices on SLM technologies (UNCCD 2016). The WOCAT team developed different standardised questionnaires in order to analyse and evaluate land management (see Liniger et al. 2019; van Haren et al. 2019; García et al. 2019; Gonzalez-Roglich et al. 2019; Giger et al. 2015; Riva et al. 2017). Two of those questionnaires were used in this study:

Core Questionnaire on SLM Technologies (QT): The purpose of the questionnaire on SLM technologies is to describe and understand the land management practices. It addresses the following

[1] Weeded/ ploughed crop (Fren.: *cultures sarclées*), also called *erosive culture* among the Haitian SRC-staff. Hereafter called either *weeded/ ploughed crop* or *conventional land management* (CLM).

questions: what are the specifications of the technology, what are the inputs and costs, where is it used (natural and human environment), and what impacts does it have? It is divided into three parts: general information, specifications, and analysis. (WOCAT 2017b)

Climate Change Adaptation Questionnaire (QCCA): This questionnaire on adaptation of SLM technologies to gradual climate changes and climate-related extremes is a supplement to QT. It assesses whether a technology is or can be further adapted to gradual climate change and climate-related extremes. The QCCA does not focus on landscapes but on individual SLM technologies. (WOCAT 2017a)

For this master thesis the technologies agroforestry, vetiver terraces and weeded/ ploughed crop (CLM) were assessed with the QT as well as the QCCA during the field trips. The questionnaires were completed with the help of Jean Carls Dessin (SLM specialist of the Haitian SRC staff) and supplemented with own field observations. After the field trips it was decided to include the technologies wattle fences for gully correction and Terra Preta raised garden beds into the analysis. Those two technologies had already been assessed with the questionnaire QT by the SRC (see Gambon 2017; Bier 2016), however not with QCCA. This is why it was not possible to compare the QCCA of all five techniques within this study. With the QT and QCCA most indicators are assessed according to predefined response categories (e.g. "no/negligible" for 0-5%, "little" for 5-20%, "medium" for 20-50%, and "high" for >50% of change). Wherever available, more detailed specifications can be included. The resulting data from the questionnaires are entered into the online WOCAT Database. Before being published, the documentations are reviewed and controlled for quality by SLM experts. Where needed, missing information is added and contradictions and ambiguities are cleared up iteratively together with the authors. The final product is a summary, which is freely accessible via the online database[2]. (Schwilch et al. 2014; Giger et al. 2015; Liniger et al. 2019)

4.1.4 Analysis of the WOCAT Questionnaires

The data gathered with the questionnaire QT were analysed based on the methodological approach of Schwilch et al. (2014), the first article to represent scientific evaluation of a set of WOCAT-documented SLM technologies and approaches. It gives an initial evaluation of how SLM addresses prevalent dryland threats. The samples of technologies assessed by Schwilch et al. (2014) and those analysed in this master thesis address similar threats: soil degradation, climate change, resource use conflicts, vegetation degradation and low production, and water scarcity. Because of the low number of samples no strict statistical comparison and analysis were possible, neither for Schwilch et al. (2014) nor for this study. Nevertheless, the compiled documentation and structured comparisons do offer insights into main common issues and major differences.

Based on Schwilch et al. (2014) and the WOCAT QT (WOCAT 2017b), the analysis was structured into the following seven sections:

[2] https://qcat.wocat.net/en/wocat/

Characterization of the selected SLM/ CLM technologies First, a quick overview on natural and human environment as well as on the main purpose and strength from land users' point of view is given. Schwilch et al. based their analysis not only on the WOCAT questionnaire QT but also on the questionnaire on SLM approaches (QA). For this master thesis, however, the approaches were not assessed. Therefore, in order to still be able to do a similar analysis as Schwilch et al. some indicators had to be replaced. This is the case for *main objective of the technology* and *land users' motivation*, which are both part of the QA. They were replaced by the QT's indicators *main purpose of the technology* and *technology's strengths from the land users' point of view*, respectively.

Impacts on water cycle Secondly, impact on the water cycle is analysed. With climate change, water availability becomes an important factor limiting food production. According to Campbell et al. (2011), annual rainfall will decrease in the future for much of the Caribbean. Schwilch et al. (2014) applies the concept of green water use efficiency (GWUE) to assess if the technologies minimise unproductive water loss while they maximise the productive flow of water. The GWUE is given by the fraction of plant transpiration over precipitation (Stroosnijder 2009). To analyse the GWUE of the documented technologies, Schwilch et al. considered following impact indicators of the WOCAT QT: *soil cover*, *soil evaporation*, *soil moisture*, and *surface runoff*. They assume that higher combined benefits across all indicators improve GWUE best. Therefore, the values[3] assigned to the impacts are added together for each practice separately. For a measurable improvement, a combined value of four or more has to be reached, in doing so the impact was high and/ or affected two or more indicators. Schwilch et al. (2014)

Impacts on soil degradation Thirdly, the technologies' impacts on soil degradation were assessed. As in Schwilch et al. (2014), this was done by the technology's influence on soil loss. Additionally, the other land degradation types addressed by the SLM technologies are listed.

Impacts of SLM and CLM on diversification and enhancement of crops In the fourth section, it is documented how the technologies impact food diversity and product enhancement. Based on Schwilch et al. (2014), this was assessed based on following indicators: *crop production*, *crop quality*, *risk of production failure*, *product diversity*, *production area* and *farm income*.

Socio-cultural benefits Fifth, the socio-cultural benefits in WOCAT QT are analysed with indicators like *food security/ self-sufficiency* or *SLM/ land degradation knowledge*. Unlike in Schwilch et al. (2014), *conflict mitigation* and *prevention of outmigration* were not relevant for this study.

Resilience towards climate change and variability In the sixth section, the CCA and DRR of the technologies were assessed. Schwilch et al. (2014) analysed the technologies' resilience towards climate change and variability only based on QT because, in 2014, the WOCAT QCCA did not exist

[3] -3 points for -50 to -100%, -2 points for -20 to -50%, -1 point for -5 to -20%, 0 points for negligible impact, 1 point for 5 to 20%, 2 points for 20 to 50%, 3 points for 50 to 100%

yet. For this thesis, however, data from the QCCA were included to complete the data gathered with QT. However, this was only possible for the technologies *agroforestry*, *vetiver terraces*, *weeded/ ploughed crop*, since the others have not been assessed with the WOCAT QCCA.

Cost-benefit analysis In the seventh and last section, the an analysis on costs and benefits were done. Schwilch et al. (2014) have a brief cost-benefit analysis of the SLM technologies. The methodological approach is, however, not entirely clear. Therefore, the cost-benefit analysis in this thesis was done following Giger et al. (2015). They analyse in detail the economic benefits and costs of SLM technologies assessed with WOCAT QT. They used quantitative and qualitative variables taken from the aforementioned questionnaire. As quantitative variables they took the *establishment costs* and the*maintenance costs*. The *establishment costs* include all initial costs that incurred when adopting the technology, such as manual labour, hire or purchase of machinery or equipment, or purchase of seedlings (Giger et al. 2015). The *maintenance costs* have been defined as the costs incurred on a regular basis to keep the technology functional (e.g. labour and costs of agricultural inputs and equipments) (Giger et al. 2015). Wherever possible the former is expressed in US dollars per hectare and latter in US dollars per hectare and year. Otherwise the costs have been given in US dollars per unit (and year). Giger et al. also analyse the *perceived cost/ benefit ratio*. In order to do that, they used four qualitative variables: the perceived short-term ratio of overall benefits to establishment costs, perceived long-term ratio of overall benefits to establishment costs, the perceived short-term benefits to maintenance costs, and the perceived long-term ration of overall benefits to maintenance costs. In WOCAT (2017b) short-term is defined as a period of 1-3 years and long-term as a period of 10 years. This four qualitative variables were expressed as discrete indexes ranging from -3 to 3, where -3 refers to a very negative and 3 to a very positive perceived cost/ benefit ratio.

4.2 Assessing the impacts of land use and land cover on potential runoff

Figure 4.1 illustrates the methodological approach for assessing the impact of land use and land cover (LULC) on the potential runoff contribution in the Cormier watershed. The main string is showed in green colour with brown arrows: first, a LULC map was created for the Cormier watershed based on a WorldView-2 satellite image, then, the runoff curve number method was applied to calculate the potential runoff. This methodological approach is based on Joss (2018). Joss analysed the impact of LULC on runoff in three watersheds in Kenya. Joss too, first created a LULC map and then calculated the potential runoff. However, unlike Joss, the land use map in this thesis was done based on an object-based instead of a pixel-based image analysis due to the high resolution of the WorldView-2 imagery. In the following sections, the work steps are presented in detail. First, however, the used input data and software are presented.

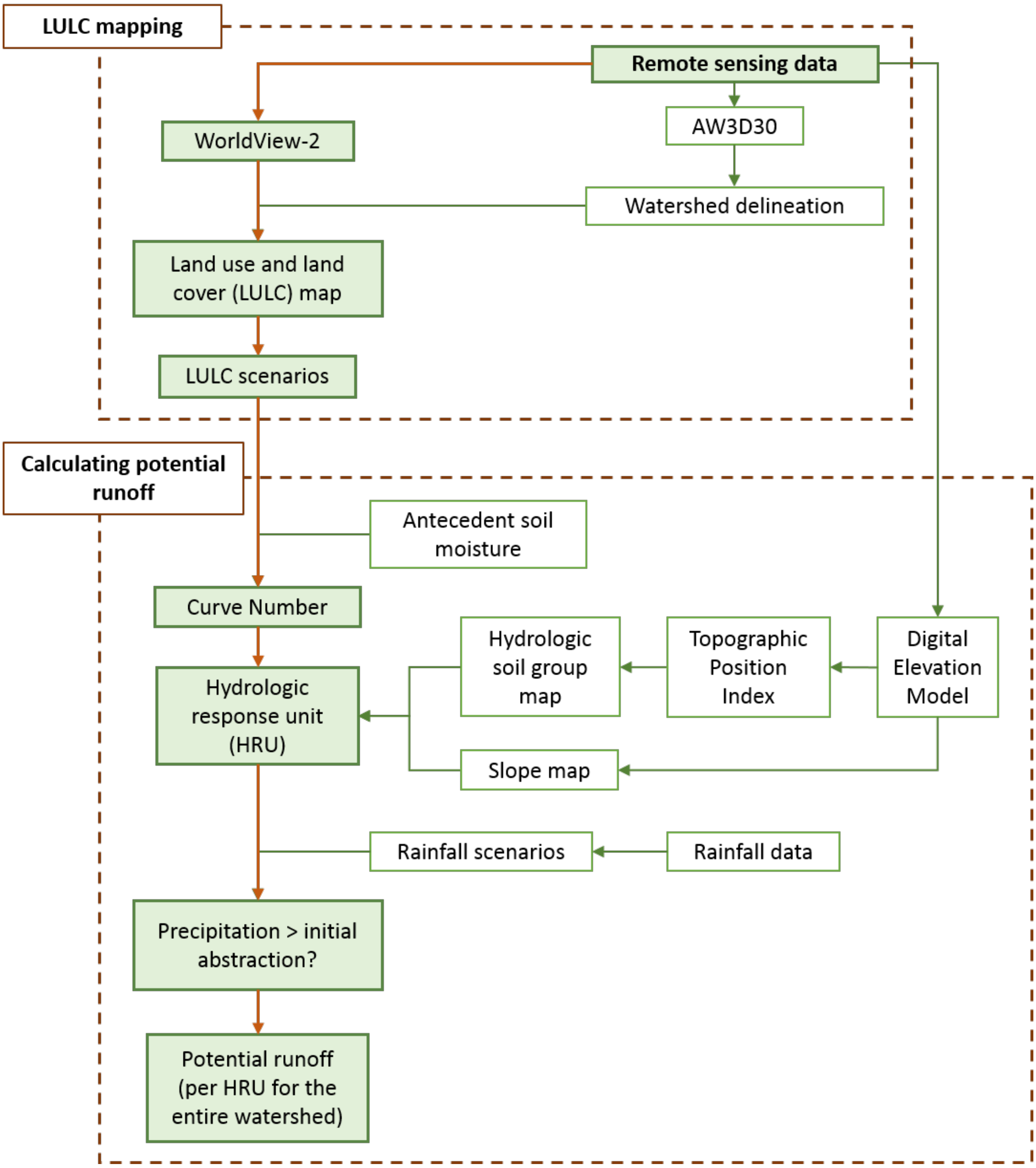

Figure 4.1: Workflow for land use mapping and potential runoff calculation

4.2.1 Data

4.2.1.1 WorldView-2 image

Requirements The selection of satellite imagery must meet the requirements for spatial and temporal resolution given by the research questions, objectives and characteristics of the region of interest. Since the Cormier watershed has an area of only 30 km^2 and small-scale farming with an average plot size of 0.5-1 ha is dominant, the spatial resolution needed to be high. Therefore, neither Sentinel nor Landsat data were an option. Moreover, in order to distinguish crop land, grass land and bare soil, the image had to be taken during or right after the rainy season, when the maximal vegetation cover is visible. In rainy season, however, it is challenging to get a good, cloud-free image.

Characteristics The purchased WorldView-2 images met the requirements of cloud-free images. WorldView-2 is a commercial earth observation satellite which provides images from a height of 770 km with a pixel size of 0.46 m for panchromatic and 1.85 m multiresolution images. The images used for this thesis were taken on the 3rd December 2017, hence, during the transition from rainy to dry season. WorldViwe-2 has eight multispectral bands: four standard colours (red, blue, green, near-infrared (NIR)) and four new colours (red edge, coastal, yellow, near-infrared2). For a simple LULC map as it is the case here, the four standard colour bands are enough. Further technical information about the WorldView-2 images is summarised in Table 4.1.

Table 4.1: Technical characteristics of the WorldView-2 images, data source DigitalGlobe (2009)

	Multispectral	**Panchromatic**
Date collected	03-12-2017	
Band(s)	4 (r, g, b, NIR)	1
Spatial resolution	1.85m	0.46m
Cloud cover	0.7%	
Off-nadir	27.5°	
Sun elevation	47.3°	
Sun azimuth	161.0°	
Sensor elevation	58.7°	
Sensor azimuth	212.0°	
Projection	UTM Zone 18 North	
Geodetic datum	WGS84	
Source	Harris MapMart	
Orthorectification	no	

4.2.1.2 Digital Elevation Model

Two different digital elevation models (DEM) were used: a digital terrain model (DTM) and a digital surface model (DSM).

Digital Terrain Model (DTM): The DTM is a set of data which represent the surface of the earth in 3D form without buildings and vegetation. For the study area a DTM provided by the Haitian national GIS agency (Centre National de l'Information Géo-Spatiale - CNIGS) was downloaded from HaitiData.org (CNIGS 2017). The HaitiData.org platform was created after the 2010 earthquake with the purpose of disseminating, sharing and exploiting geographic information system (GIS) and cartographic data about Haiti. The CNIGS is in charge of the platform. Data shared on HaitiData.org is accessible to the general public. It therefore improves exchange and collaboration between NGOs, ministries, the international community, academia and the private sector. (HaitiData.org n.d.). With a pixel size of 1.5 m, the resolution of this DTM is very high. In this thesis, it was used to generate the slope map as well as the hydrological soil group (HSG) map. However, it was unsuitable for the

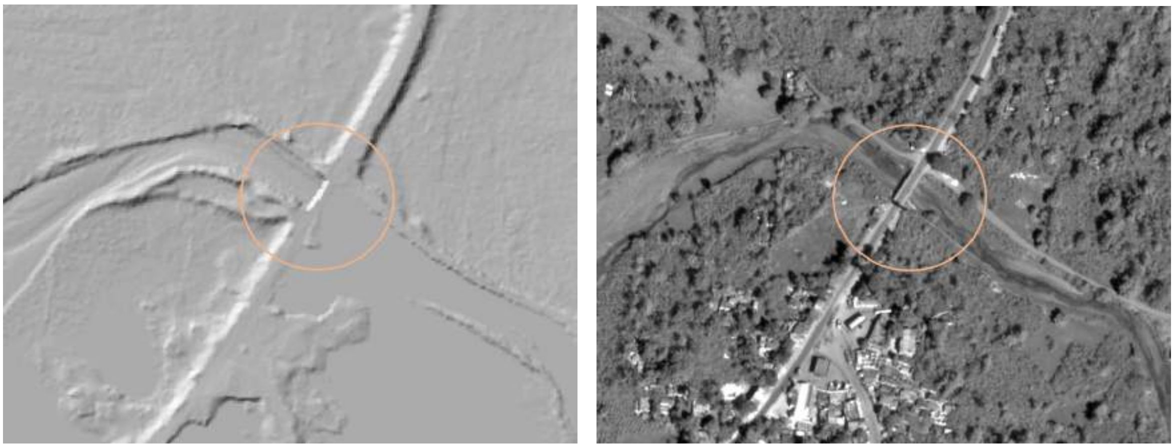

Figure 4.2: Erroneous digital elevation model: bridge of the *Route Nationale 2* over the Cormier river as depicted in the DTM hillshade (l.) and in the WorldView-2 panchromatic image (r.).

watershed delineation in ArcMap because of the bridge of the *Route Nationale 2*, which crosses the Cormier river in the lower zone of the watershed. As shown in Figure 4.2, in the DTM the river is erroneously cut off by the bridge. When delineating the watershed with this DTM, the river ends at the bridge, when in reality it would pass under the bridge and continue to flow. Therefore, a coarser DEM was needed for this step.

Digital Surface Model (DSM) For the watershed delineation a coarser elevation model like "ALOS World 3D - 30m (AW3D30)" was needed. This is a DSM, an earth surface model, which includes objects (e.g. houses, bridges etc.) on it. "ALOS World 3D - 30m (AW3D30)" has a resolution of approximately 30-meter. Due to this coarse resolution, little objects, such as the *Route Nationale 2* bridge, were no relevant obstacles. Therefore, this free DSM provided by the Japan Aerospace Exploration Agency (JAXA) was used to delineate the Cormier watershed.

4.2.1.3 Rainfall data

There are monthly and annual rainfall data available for Léogâne (see Chap. 2.2.1). The curve number model, however, is an event-based calculation and should not be used for a single month or annual rainfall as this will incorrectly miss the effect of the antecedent soil moisture condition as well as the necessity of an initial abstraction threshold. Since there was no daily rainfall data available for Léogâne, data from another region had to be used. For Camp-Perrin (Cayes) a dataset covering daily rainfall amounts from 1993 - 2010 is available (ORE). Camp-Perrin is a village about 130 km west from Léogâne and located at 250m above sea level. The annual rainfall is about 2160mm and therefore much higher compared to Léogâne (1400-1500mm). However, the Cormier watershed is mostly at higher altitude and, as mentioned in Chapter 2.2.1, the upper zone of the Cormier watershed is more humid. Therefore, it is assumed that the rainfall amounts are comparable. Moreover, due to the fact that data availability is a big challenge for research in Haiti, this was the only option. In 2007, there is a data gap from May-Dec, hence, it was excluded from further analysis. For the data covering the other years (1993-2006 and 2008-2010) the 50, 75 and 95 percentile as well as the 2 and 10yrs return period were derived (see Tab.4.2). As an additional extreme event the

Table 4.2: Precipitation scenarios

Definition	Precipitation	Rounded precipitation	Scenario name
50-percentile	8	8	$P8$
75-percentile	20	20	$P20$
95-percentile	68	70	$P70$
2yrs return period	150	150	$P150$
10yrs return period	297	300	$P300$
Hurricane Matthew	519	500	$P500$

rainfall amount of the hurricane Matthew was included. This category 4 hurricane made landfall over Haiti on 4th October 2016. Satellite-based estimations done by the Netherlands Red Cross resulted in over 500 mm rainfall for that day in certain communes of Haiti (Netherlands Red Cross 2016).

4.2.2 Used software

For this research question three computer-based applications were used: eCognition Developer, ENVI and ArcMap. eCognition is used in particular for mapping, recognition of changes and for the object recognition, so that standardized and reproducible results of the image analysis are possible. Trimble Germany GmbH's **eCognition Developer** (version 9.3) is one of three software components that provide a developer environment for object-based image analysis. Through this approach, the WorldView-2 image was subjected to an object-based analysis and thus to a segmentation and classification.

The calculation of texture [4] feature *texture after Haralick* for the feature space optimization in eCognition (see Chap. 4.2.3.3) was too time consuming. In order to save time, the texture was calculated with **ENVI** (version 5.5), an image analysis software used in remote sensing, which provides various texture filters. The results were then exported as tiff files and imported in eCognition as image layers.

ArcGIS is a generic term for ESRI's GIS software products. **ArcMap** (version 10.6) is the main application of the ArcGIS Desktop suite and used for creating, editing, and processing geospatial data. The versatility of the program is also reflected in its use in this work. The program was used for various tasks: pre-processing the WorldView-2 image, delineating the watershed, accuracy checking of classification, generating slope and hydrological soil group map, and visualizing the results.

4.2.3 Land use and land cover mapping

In this section the first step of the methodological approach of the research question Q2 is presented: the LULC mapping based on the WorldView-2 images. This was done in five working steps. First, the WorldView-2 images were pre-processed and then the LULC categories were defined within a

[4] Texture is the optical impression of coarseness or smoothness of a image. It is caused by the variability or uniformity of the image tone or colour.

classification scheme. Subsequently, the classification was carried out by means of an object-based method and an accuracy assessment was carried out.

4.2.3.1 Data pre-processing

Before processing the WorldView-2 images in eCoginiton, they had to be orthorectified, pansharpened and clipped to the extent of the Cormier watershed.

Orthorectification In practice, satellite sensors do not collect images at nadir (looking straight down at the target). They always shoot at an angle. Any point not directly beneath the scanner's detectors, but rather off at an angle is called "off-nadir". The process of stretching the satellite image to match the spatial accuracy of the map (considering elevation, location, and sensor information) is called orthorectification. This can be done in ArcMap using the *Orthorectify* function. The WorldView-2 images purchased have an off-nadir angle of 27.5°, which is extremely oblique for this predominately mountainous area. Therefore, the images were strongly distorted after the orthorectification. Especially the north facing slopes got distorted since the images were recorded from the south-west (sensor azimuth 212°). Moreover, the sunlight was coming from the south (sun azimuth 161°) with an inclined incidence angle (sun elevation 47.3°), throwing shadows on the distorted north facing slopes.

Pan-sharpening As shown in Tab. 4.1, the panchromatic WorldView-2 image has higher spatial resolution than the multispectral image. Pan-sharpening (or panchromatic sharpening) is the process of fusing a higher-resolution panchromatic raster layer with a lower-resolution multispectral layer. The result produces a multispectral raster layer with the resolution of the panchromatic raster where the two raster layers fully overlap. One of the main reasons for configuring satellite sensors in this way is to minimize the weight, cost, bandwidth and complexity of the satellite. Also for this pre-processing step there is a function in ArcMap.

Clipping to watershed Since computing speed depends on the number of base units (Chap. 3.3.4), the orthorectified and pan-sharpened satellite image was clipped to the area of the Cormier watershed. A watershed is physically delineated by the area upstream from a specified outlet point. The watershed delineation was done in ArcMap with the DEM following the instruction of MaDGIC (2014). Subsequently, the satellite image was cut to the extent of the Cormier watershed with the clipping tool in ArcMap.

4.2.3.2 Classification scheme

The classification scheme defines the LULC categories relevant for the research question. According to Jensen (2015), there are three requirements which need to be considered when determining these categories: they should be complete, not overlap taxonomically, and have a hierarchical structure. In practice, however, the implementation of these conditions can be challenging. For instance, although hard boundaries between the categories are demanded, blurred transitions often prevail in reality. Another problem are the classification schemes with mixed land use and land cover. This practice is often discussed and questioned, but common (Comber et al. 2008; Huerlimann 2019).

The described challenges are also reflected in the present thesis. The developed classification scheme consists of a mixture of land use and land cover categories, which are not determined conclusively but complemented and substantiated in the course of the iterative classification process. Originally, it was planned to use the newly developed *WOCAT Watershed and Runoff Tool* (Liniger et al. in prep.), a QGIS based script for hydrologic modelling of watersheds using the runoff curve number model. However, the LULC categories used in this tool are too broad. Therefore, some categories were based on the classification scheme of MacMillan (unpublished), which focuses on the hydrologic influence of vegetation on runoff contribution, evaporation and interception. MacMillan distinguishes the classes by canopy and primary vegetation cover. This helps to better represent the land cover observed in the field. MacMillan's land cover categories were developed for the Ewaso Ng'iro basin in Kenya. Where needed, adaptations were done.

Table 4.3 shows the developed schemes with land use and land cover categories, including the specific criteria used to taxonomically delineate the categories.

Table 4.3: Used classification scheme based on MacMillan (unpublished) and the WOCAT Watershed and Runoff Tool (Liniger et al. in prep.)

Abbr.	LULC classes	Criteria
Td	Forest, dense trees	20-50% tree/ bush canopy
TG/TC	Dense agroforestry	20-50% tree/bush canopy, grass/ crop as primary cover (good condition)
tG/tC	Agroforestry	$\leq$ 20% tree/ bush canopy, grass/ crop as primary cover (good condition)
G/C	Grass / crop	grass/ crop (good condition), no tree/ bush (NDVI $>$ 0.55)
Cp	Perennial crop	Pigeon peas, sugar cane, banana etc., no tree/ bush
TGs/TCs	Dense Agroforestry with sparse grass/ crops	20-50% tree/bush canopy, grass/ crop as primary cover (poor condition)
tGs/tCs	Agroforestry with sparse grass/ crops	$\leq$ 20% tree/ bush canopy, grass/ crop as primary cover (poor condition)
Gs/Cs	Sparse grass/ crops	grass/ crop (fair condition), no tree/ bush (0.4 $<$ NDVI $\leq$ 0.55)
Gb	Bare soil, very sparse grass/crop	grass/ crop (poor condition), no tree/ bush (NDVI $\leq$ 0.4)
S	Sand mine	Thematic layer created manually
U	Urban area	Roads and settlement, thematic layer created manually
W	Water	Riverbed and ponds, thematic layer created manually
ET	Earth terraces	Thematic layer created manually

With the available spatial resolution and spectral bands of the WorldView-2 satellite image, it was not possible to distinguish between the classes grass and crop, so they were classified together. Actually, there are not many grasslands in the Cormier watershed. People in the region do not have many animals and the ones they have are kept tied to a tree or a peg when letting them graze. Most of the grass cover is found on fallow land where usually the technology of weeded/ ploughed crops (CLM) is applied (see Fig. 4.3). In USDA-SCS (1985) separation between good, fair(sparse) and poor grass/ crop cover (here G/C, Gs/Cs, and Gb respectively) is given by the cover thresholds >75% (=good), 50-75% (=fair), and <50% (=poor). In this thesis, the separation was done on trial and error by adjusting the Normalized Difference Vegetation Index (NDVI) in order to estimate these given thresholds. The last four categories were done by hand since it was too difficult to distinguish them automatically from other categories. On the one hand, the dry riverbed, the sand mine, the earth terraces were difficult to distinguish from bare soil (Gb) because they do not have vegetation cover. On the other hand, the ponds have water plants on the surface and therefore show abnormally high NDVI values compared to water. Normally, thematic layers are used in GEOBIA for simplifying the classification of these classes (river, water, roads, etc.), but there were none available for the study area. Therefore, the classes *Sand*, *Urban*, *Water* and *Earth terraces* were created manually after the image segmentation in eCognition and subsequently added as thematic layers.

Figure 4.3: Fallow of conventional land management as grassland: most of the grass cover is found on fallow land of conventional land management (CLM, the technology of weeded/ ploughed crops). Therefore, the characteristic ploughing lines and signs of soil degradation are clearly visible. (Photo: HP. Liniger 2017)

4.2.3.3 GEOBIA

As mentioned in Chapter 3.3.4, the improving resolution of satellite images has led to a paradigm shift from pixel-based to object-based image analysis. Therefore, unlike (Joss 2018), who analysed Sentinel-2 imagery with a resolution of 10m, it was opted to use the object-based image analysis for this thesis. The geographic object-based classification was done with the software eCognition in two steps: fist, the image is segmented into homogenous image-objects, then these image-objects are classified according to the classification scheme.

Segmentation

In the process step of segmentation, the image is divided into homogeneous regions, the image-objects. This structure forms the basis of the object-based classification and is central to further processing. eCognition provides different segmentation algorithms. In this study, the multiresolution segmentation algorithm is used. This widely used region-based technique creates image-objects using an iterative algorithm, whereby image-objects (starting with individual pixels on Level 1) are grouped until the homogeneity/ heterogeneity criterion is satisfied. It is therefore a bottom up approach. The multiresolution segmentation algorithm considers both spectral (colour) and spatial (shape) homogeneity of objects. By weighting the image layers on their importance or suitability, the segmentation results can be adjusted. (Salehi et al. 2012). Additionally, eCognition allows the user to set the three key parameter *scale*, *shape*, and *compactness* (Trimble 2018a):

- **Scale** is the most crucial parameter and controls the average size of the image-objects Salehi et al. (2012). The optimal size depends on the research question. If the objects are too small or too big, important information for latter classification may get lost.
- The **shape** parameter defines the relationship between shape and colour criteria. Decreasing the shape value results in spectral (colour) information of the image becoming more dominant (spectral homogeneity). In contrast, at high levels, objects will be more optimized for spatial homogeneity.
- The **compactness** parameter is used to better separate compact objects with low spectral contrast from neighbouring objects. Higher compactness values tend to lead to compact image-objects and less frayed object edges.

Finding the optimal parameters for segmentation is a trial and error process. It is very time consuming and depends directly on the users' experience. (Salehi et al. 2012)

The settings found by trial and error for the segmentation in this thesis are shown in Table 4.4. The input layers were the pan-sharpened WorldView-2 image with the four multispectral bands and a NDVI layer generated in eCongition based on that same image. The optimal settings of the parameters scale, shape and compactness were selected based on the visual analysis of different combinations. Experience has shown that the land use and land cover categories to be classified differed mainly by their spectral properties. The shape parameter therefore had to be chosen low. Subsequently, as mentioned before, the roads, settlements, riverbed, ponds, sand mines, and earth terraces were classified manually. This was done on Level 1 (segmentation based on individual pixels) and Level

Table 4.4: Overview on segmentation levels and used parameters

Processing level	Level 1	Level 2	Level 3
Segmentation based on	pixel	image-object	image-object
Parameter settings			
- scale	30	45	55
- shape	0.1	0.1	0.3
- compactness	0.8	0.7	0.7
Layer weighting			
- red	2	2	2
- green	3	3	3
- blue	1	1	1
- NIR	3	3	3
- NDVI	3	3	3

2 (segmentation based on the image objects resulted in Level 1). On the remaining unclassified objects, a third segmentation was executed (Level 3, segmentation based on image-objects from Level 2).

Nearest Neighbour Classification

After image segmentation, the classification of the image-objects took place. There are different classification procedures. Basically, a distinction is made between manual and automatic classification methods. Given the high level of the mosaic-like structure of the LULC a purely manual classification was out of the question for the respective research question as this would be too time-consuming. This is another reason for not having used the WOCAT Watershed and Runoff Tool, which currently only works with the manual classification approach.

For these reasons, the nearest neighbour classification was used in this master thesis. As described in the eCognition User Guide (Trimble 2018b), the procedure is a supervised classification in which training areas (samples) are determined for each LULC categories. Subsequently, the objects are automatically assigned to the defined classes on the basis of similarities - in this case using the nearest neighbour method.

Selection of training samples

The quality of the classification depends decisively on the choice of training areas. On the one hand, these must be homogeneous and representative of the respective class, and on the other hand must take account of the dispersion within the categories. The information can be obtained from the image itself, from maps or by means of an area survey (Schmidt 2000). For this thesis, the samples were determined directly on the basis of the WorldView-2 image since this research question was developed after the field trip and there was no other cost efficient option at this research stage.

Optimizing the feature space

After selecting the training areas, the so-called *feature space* was set. The feature space consists of a combination of features, e.g. *spectral property* or *texture* that distinguishes the categories from each other, and later assigns the objects to the categories. eCognition offers a large selection of such features. In addition, further user-specific features can be created. With *feature space optimization*, eCognition offers a tool that automatically identifies the most suitable combination for separating classes from a selected set of features (Trimble 2018b). In this thesis, a total of 41 features of different feature groups and subgroups were tested for their best combination to determine feature space. The selection was done based on Leduc (2004), visual inspection of all calculated features and examination of the separability of the defined LULC classes. In the following only the user-specific features will be explained. However, all 41 used features are listed in the Appendix 6.3). The textures calculated in ENVI were exported as tiff files and imported in eCognition as image layers. Hence it was possible to include their mean or standard deviation values for the feature space optimization.

In remote sensing, spectral indices[5] are widely used to visualize information that was not visible when viewing individual bands. The following five indices algorithms were included as user-specific features in order to improve the separability of the classes:

NDVI: Green vegetation, dead or senescent vegetation and dry bare soil have unique spectral signatures. Based on these characteristic absorbing and reflecting wavelengths patterns different vegetation indexes were created (Jensen 2015). The normalized difference vegetation index (NDVI) is widely accepted as a good proxy indicator of the degradation of vegetation as well as land degradation in general (Jensen 2015; Bai et al. 2008; Gonzalez-Roglich et al. 2019; García et al. 2019). It is defined by combining the values of near-infrared (NIR) and red spectral band (red) as follows (Jensen 2015):

$$NDVI = \frac{NIR - red}{NIR + red} \tag{4.1}$$

The NDVI, however, is sensitive to soil background and atmospheric effect. Therefore, new indices were developed:

EVI The enhanced vegetation index (EVI) was developed by Liu and Huete (1995) and provides improved sensitivity in regions of high biomass while minimizing the effects of soil and atmosphere (Ahmad 2012). It is limited to sensor systems that have a blue band in addition to the red and near-infrared bands, making it difficult to create long-term EVI time series as a counterpart to the Normalized Difference Vegetation Index (NDVI). For this study, however, blue band was available. The EVI is defined as follows:

$$EVI = 2.5 \times \frac{NIR - red}{1 + NIR + 6 \times red - 7.5 \times blue} \tag{4.2}$$

SAVI: Lack of vegetation implies weaker signals for remote sensing of vegetation. Additionally, the more soil is sensed, the fuzzier the results become when using only conventional vegetation indexes such as NDVI. The soil-adjusted index (SAVI) fills this gap. The SAVI was defined by Huete (1988) as follows:

$$SAVI = (1 + L) \times \frac{NIR - red}{NIR + red + L} \tag{4.3}$$

where L (soil-brightness correction factor) is 1 for low, 0.5 for intermediate and 0.25 for high vegetation. Normally, L has to be specified through trial-and-error based on the amount of vegetation in the study area. For simplicity, the majority of researches end up using the intermediate L (0.5) (Ahmad 2012) as it was done in this study.

[5]Spectral indices refer to mathematical operations based on different combinations of the spectral reflectance values of each pixel

MSAVI2: The modified soil-adjusted vegetation index was developped by Qi et al. (1994) in order to more reliably and easily calculate the soil brightness correction factor L (Ahmad 2012). The MSAVI2 is obtained by:

$$MSAVI = \frac{2 \times NIR + 1 - \sqrt{(2 \times NIR + 1)^2 - 8 \times (NIR - red)}}{2} \tag{4.4}$$

OSAVI: Rondeaux et al. (1996) developed an optimized soil-adjusted vegetation index (OSAVI) which easily out-performed all other indices for application to agricultural surfaces. OSAVI is calculated as follows:

$$OSAVI = \frac{NIR - red}{NIR + R + 0.16} \tag{4.5}$$

4.2.3.4 Accuracy Assessment

"The need for assessing the accuracy of a map generated from any remotely sensed data has become universally recognized as an integral project component" (Congalton 2004, p. 1). Classification results derived from remote sensing data are usually flawed. The imperfections can accumulate during data collection, processing and later conversions. For the assessment of the quality of the LULC map, the classification results are therefore subject to validation. This offers the possibility to detect and minimise errors. Moreover, the later user is informed about the quality of the classification. (Jensen 2015).

While a pixel-based image analysis only addresses the thematic accuracy - the assignment to a LULC category - GEOBIA can assess both thematic and geometric accuracy. The latter assesses how well shape, position and edge of the extracted objects is in line with reality (Lizarazo 2014). However, since the focus of the present work is not on the image classification itself, but rather on the following modelling of LULC's potential runoff contribution, the evaluation of geometric accuracy is waived.

Sample design

In this thesis, the thematic accuracy was checked using a confusion of error matrix created with the *Compute Confusion Matrix Tool* in ArcMap. This tool compares the results of classification with selected reference data. Reference data are classified data that are considered to be correct (real). It is common to obtain the reference data from sources considered "more accurate" than the original source. Sometimes surveys using GPS are required, in other situations a map with higher resolution is sufficient. (Congalton 2015). The National Standard for Spatial Data Accuracy (NSSDA) suggests the reference data be "of the highest accuracy that is feasible and practical" (FGDC, p. 3f.).

As mentioned before, this research question was assessed after the field trip. Therefore, the reference data was collected using a manual classification method and when needed Google Earth images were consulted. The number of samples for the reference data depends on the number of thematic classes. According to Congalton (1988), 50 samples per class are suitable for most maps with less than 5'000 km^2. The samples were randomly selected in ArcMap using the *Create*

Accuracy Assessment Points Tool with the stratified random sampling scheme. The advantage of the method lies in the fact that also samples of classes with a very small surface area are guaranteed. The LULC map resulted from this study had 10 LULC classes[6], which resulted in about 500 samples.

Confusion Matrix

The *Compute Confusion Matrix Tool* in ArcMap calculates user and producer accuracy for each class, overall accuracy, and a common kappa match index. These accuracy rates range from zero to one, with one representing an accuracy of 100%. For this, the correctly and incorrectly classified pixels of each class are listed in tabular form (see Tab. 5.6). The above-mentioned evaluation measures are defined and calculated as follows (Congalton 2015; Jamil 2010):

- The **overall accuracy** is formed by dividing the sum of all correctly mapped sample units (major diagonal of the error matrix) by the total number of sample units.
- The **producer's accuracy** is calculated from the correctly classified sample units of a class divided by the total number of reference units of the respective class. It determines the probability with which a reference sample unit is correctly classified.
- The **user's accuracy** is computed by the correctly classified samples units divided by the total number of sample units of the respective class. It expresses the probability that a sample unit of the same class belongs to the reference data.
- The **Kappa-coefficient** indirectly includes the errors in the calculation of statistics by using the sums of row and column sums. It is a measure of the overall accuracy and assumes that the created and the reference classification are of equal reliability. It shows how well the classification results match the reference data.

4.2.4 Calculating the potential runoff contribution

4.2.4.1 The SCS Runoff Curve Number Method

Joss (2018) determined the impact of land use and land cover on the rainfall runoff contribution in the lower Ewaso Ng'iro basin (Kenya) by applying the Soil Conservation Service Curve Number (SCS-CN) method (USDA 1972). Estimating runoff in data scarce areas is a challenge. There are different methods available for estimation of rainfall runoff: e.g. the *Green Ampt* method, the *Rational* method, and the *Soil Conservation Service Curve Number* method (SCS-CN). The Green-Ampt method (Heber Green and Ampt 1911) is a process based method. The infiltration is estimated using the soil suction head, porosity, hydraulic conductivity and time. The Rational method (Kuichling 1889) and the SCS-CN are both empirical equations. The Rational method was developed for small drainage basins (smaller than 80ha) in urban areas. The runoff is estimated based on the soil type and drainage basin slope. Based on the methodological approach of Joss (2018), the SCS-CN

[6] 10 classes if taking all classes done manually (water, roads, settlements, earth terraces) together as one.

method was also used in this thesis. The SCS-CN method was developed by the US Department of Agriculture (USDA 1972) and is widely accepted (Gitika and Ranjan 2014; Matomela et al. 2019; Huang et al. 2006). The SCS-CN is an empirical parameter and predicts the potential surface runoff volume from a single rainfall event. Hence, it should not be used for estimating the annual runoff of a watershed, as this will incorrectly miss the effects of antecedent moisture and the necessity of an initial abstraction threshold. According to the National Engineering Handbook, Section 4, Hydrology (USDA-SCS 1985), the runoff Q [mm] can be derived from the following equation:

$$Q = \frac{(P - I_a)^2}{(P - I_a) + S} \tag{4.6}$$

where

- Q = runoff [mm]
- P = rainfall [mm]
- S = potential maximum retention after runoff begins [mm] and
- I_a = initial abstraction [mm]

Joss (2018) was also confronted with data scarcity. Since no weather stations were located in his study area, Joss (2018) opted for rainfall data from weather satellites. However, these were monthly precipitation data. The SCS-CN model, however, is an event-based calculation and should not be used for a single month or annual rainfall as this incorrectly misses the effect of the antecedent soil moisture condition and the initial abstraction threshold. The initial abstraction includes infiltration, evaporation, water absorbed by vegetation, and water retained in surface depressions. Empirical studies showed that I_a can be approximated by following equation (USDA-SCS 1985):

$$I_a = 0.2S \tag{4.7}$$

Substituting Equation (4.7) into (4.6) gives:

$$Q = \frac{(P - 0.2S)^2}{P - 0.8S} \qquad \text{for } P > I_a \tag{4.8a}$$

$$Q = 0 \qquad \text{for } P \leq I_a \tag{4.8b}$$

The value of S, the retention parameter, is obtained from:

$$S = \frac{25400}{CN} - 254 \tag{4.9}$$

The curve number CN rages from 0 (minimum runoff) to 100 (maximum runoff) (USDA 1972). The value in Equation (4.9) describes average antecedent soil moisture (AMC) and is also referred as

CN_2. Other AMC can be derived from the initial CN_2, with CN_1 for dry conditions and CN_3 for wet conditions (Equations (4.10a) and (4.10b)):

$$CN_1 = CN_2 - \frac{100 - CN_2}{100 - CN_2 + e^{(2.533 - 0.0636 \times (100 - CN_2))}} \tag{4.10a}$$

$$CN_3 = CN_2 \times e^{(0.00673 \times (100 - CN_2))} \tag{4.10b}$$

The CN by USDA (1972) is assumed to correspond to a slope of 5% (Huang et al. 2006; Sharpley and Williams 1990). Sharpley and Williams (1990) applied an approach to estimate a slope-adjusted curve number. However, this approach was never intensively verified in the field (Huang et al. 2006). Later, Huang et al. adopted a simplified approach and tested it in an experimental watershed in China. Recently, Ajmal et al. (2016) modified their approaches and validated its efficacy for South Korean watersheds. Verma et al. (2018) compared these three different slope-adjusted curve number values and concluded that the Sharpley and Williams' approach performed the best. According to Verma et al. (2018), incorporation of slope factor in the model might be the reason. Sharpley and Williams (1990) slope-adjusted CN_2, named $CN_{2\alpha}$, is obtained by

$$CN_{2\alpha} = \frac{1}{3}(CN_3 - CN_2)(1 - 2e^{-13.86\alpha}) + CN_2 \tag{4.11}$$

where CN_2 and CN_3 are the SCS-CN for AMC-II (average) and AMC-III (wet), and α [mm^{-1}] is the slope. Joss (2018) did not differentiate in soil moisture condition; he used the average condition for calculating runoff in both dry season and wet season conditions. For the present study, however, $CN_{1\alpha}$ and $CN_{3\alpha}$ are obtained by replacing CN_2 with $CN_{2\alpha}$ in the Equations (4.10a) and (4.10b) as suggested by Gitika and Ranjan (2014).

Following major factors determine the SCS-CN: hydrologic soil group (HSG), land cover, treatment, hydrologic condition, and antecedent soil moisture (AMC). The following sections explain these factors and how they were used in this study.

Hydrologic soil group (A, B, C, D)

According the SCS-CN method, soils are divided into four hydrologic soil groups (HSG), which indicate the minimum infiltration rate after prolonged wetting USDA-SCS (1985):

A Soils with low runoff potential and high infiltration rate belong to group A. They usually consist of sand or gravel and remain permeable even when completely wetted.

B Soils that belong to group B have a moderate infiltration when they are wet and often consist of silt loam or loam.

C Group C soils have low infiltration when thoroughly wetted. They consist of clay or loam layers. This impedes the downward movement of the water.

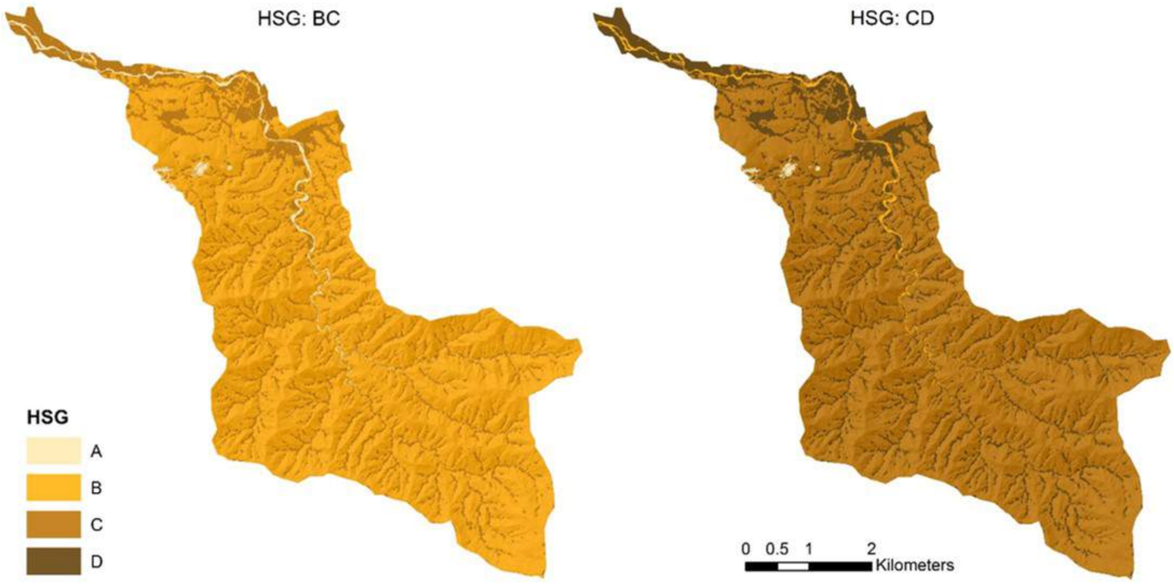

Figure 4.4: Hydrologic soil group (HSG) maps created in ArcGIS with the topographic position index (TPI) tool: scenario with higher (HSG BC) and lower (HSG CD) infiltration potential

D These soils are likely to generate the highest runoff. They consist mainly of clay, hence, they have a high swelling potential. They have nearly no infiltration when thoroughly wetted.

There is a global HSG dataset (HYSOGs250m) available with a 250 m resolution (Ross et al. 2018). According to this dataset, the soils in the study area belong to HSG C and D, whereas the latter is especially dominant in the lower zone of the watershed. This classification can be explained by the fact that soils resulting from basaltic parent material tend to be clay-rich (Lentini and Di Crecco 04.2012). Nevertheless, as mentioned before in Chapter 2.2.3, Ferralsols and Cambisols, the two dominant soil types in the mountainous areas of Léogâne, have a rather good water infiltration and drainage rate. Therefore, an alternative HSG map was created with more permeable HSGs: B and C. This was done in ArcMap with the *Topographic Position Index Tool*. With the topographic position index (TPI) tool, users can classify the landscape based on a digital elevation model into topographic position (e.g. valley, slope, ridge). Taking into account that fine soil material is washed away on slopes and ridges and accumulated on valleys, depressions and plains, plains, valleys, and lower slopes (slope < 5%) were assigned to group C and slopes (> 5%) and ridges to B. As the name suggest, sand mining area consist of sand, hence, they belong to HSG A. Although TPI indicates the riverbed to be a valley, the HSG for the riverbed was changed to A. It was assumed that most of the finer material is washed into the sea and sand and gravel stay in the riverbed. In order to be able to compare the influence of the HSG on the runoff, an additional scenario was done with the hydrologic soil groups D for valleys, slight slopes (< 5%) and plains, C for steeper slopes (> 5%) and ridges, and B for the Riverbed and sand mining area. The two HSG maps are represented in Figure 4.4.

Land cover, treatment, hydrologic condition

Land cover types have a big impact on the CN. Urban areas, for instance, are impervious surfaces and increase runoff. There are different methods to determine cover type, for instance, aerial photos or land us maps. The **treatment** is a modifier of the cover type and describes the land use management of cultivated agricultures. It includes practices such as terracing, contouring, crop rotation and no tillage. The **hydrologic condition** indicates the effect vegetation cover has on infiltration and runoff and is usually estimated by the density of plant and residue cover. Good hydrologic condition refers to soils which usually have a low runoff potential for the particular hydrological soil group, the type of cover and the treatment. The following factors need to be taken into account when estimating the impact of vegetation cover on infiltration and runoff: a) canopy or density of vegetation; b) amount of year-round cover; c) amount of grass or close-seeded legumes in rotation; d) percentage of residue cover; and e) degree of surface roughness. The threshold value of what is considered poor, fair and good hydrologic condition varies depending on the land cover class. According to USDA-SCS (1985), for grassland a grass cover of 75% or higher is needed for a good hydrologic condition. A 50-75% cover represent fair and less than 50% poor hydrologic conditions. USDA-SCS (1985)

As mentioned before, in this thesis, an object-based image analysis was done for LULC mapping. The used LULC classes are shown in Table 4.3. The hydrologic condition was included in the classification scheme: Gb and all categories with "s" (sparse) at the end represent poor hydrologic condition, the rest good condition. The conventional land management (CLM) with ploughed and weeded crop is widely spread in the Cormier watershed. Therefore, the CN for grass/ crop (G/C) was adapted to contouring, but not to terracing since the CLM ridges are done with lose soil.

Antecedent soil moisture condition

The **antecedent soil moisture condition** (AMC), also called the *antecedent runoff condition*, was used in the National Engineering Handbook (USDA 1972) for referring to the antecedent 5-day rainfall. It is divided into three levels: AMC-I for dry condition, AMC-II for average condition, and AMC-III for wet condition in a watershed. The higher the AMC, the higher the CN, hence, the higher the runoff potential is. (Mishra et al. 2004)

In order to analyse the off-site impacts of current land management practices within the watershed, all three different soil moisture conditions were assessed: dry condition for the period at the end of the dry season, wet condition for the end of the rainy season and average soil moisture condition for the first two month of the rainy season (see Tab.4.5).

Table 4.5: Specifications for the scenarios with current land use and land cover (LULC) for dry (I), average (II) and wet (III) antecedent soil moisture condition (AMC)

Name	LULC	AMC
$LULC_{dry}$	dry	I
$LULC_{avrg}$	$original$	II
$LULC_{wet}$	$original$	III

For simulating the condition at the end of the dry season not only the dry AMC was chosen but also the LULC was slightly adapted. Leaning on Google Earth images of January-March, good hydrologic conditions were changed to poor ones. The dry riverbed was changed to bare soil (Gb) and the dried up ponds were changed to grass/ crop (with good hydrologic condition, though).

4.2.4.2 Curve Number assignment

In order to use the SCS-CN method, a CN_2 value has to be assigned to each class assessed in the LULC mapping. Since this thesis does not include any field experiments, well documented CN_2 values in literature were used for the definition. As explained in Chapter 4.2.3.2, the LULC classes for the Cormier watershed were based on the WOCAT Watershed and Runoff Tool (Liniger et al. in prep.) and MacMillan (unpublished). Table 4.6 shows the final assigned CN_2 for each class used in the scenario with the current LULC. For detailed LULC classes and corresponding CN_2 values for each scenario, see Appendix 6.3.

Table 4.6: Assignment of the CN_2 to the LULC classes for scenario $LULC_{now}$

Land use type	Abb.	Hydrologic Condition	HSG				Specifications; source
			A	B	C	D	
Urban	U	–	74	84	90	92	roads, houses; MacMillan: $Urban$
Water	W	–	95	95	95	95	waterbodies (riverbed and ponds); MacMillan: $Water$
Earth terraces	ET	poor/fair	55	71	79	84	big earth terraces for slope stabilisation $= 0.5 * Ca_{cont,terr,good} + 0.5 * Ge_{fair}$
Sand mine	S	poor	68	80	87	91	sand mine; WOCAT: Ge_{poor}
Bare soil	Gb	poor	68	80	87	91	grassland, bare; WOCAT: Ge_{poor}
Sparse grass/ crop	$Gs\&Cs$	poor/fair	58	74	82	87	$= 0.5 * Gs + 0.5 * Cs$
Grass/ crop	$G\&C$	good	51	68	78	84	$= 0.5 * G + 0.5 * C$
Perennial crop	Cp	good	55	69	78	83	perennial crop (contoured,good); WOCAT: $Cp_{cont,good}$
Agroforestry with sparse grass/ crop	$tGs\&tCs$	poor/fair	58	73	81	86	Agroforestry (<20% trees) with sparse grass or bare soil (Gb), $= 0.2 * Td + 0.8 * Gb$; MacMillan, adapted
Agroforestry with grass/ crop	$tG\&tC$	good	44	64	74	80	Agroforestry (<20% trees) with good grass/crop ($G\&C$), $= 0.2 * Td + 0.8 * G\&C$; MacMillan, adapted
Dense agroforestry with sparse grass/ crop	$TGs\&TCs$	poor/fair	48	67	75	81	Agroforestry (<50% trees) with sparse grass or bare soil (Gb), $= 0.4 * Td + 0.6 * Gb$; MacMillan, adapted
Dense agroforestry with grass/ crop	$TG\&TC$	good	38	60	70	76	Agroforestry (<50% trees) with good grass/crop ($G\&C$), $= 0.4 * Td + 0.6 * G\&C$; MacMillan, adapted
Forest	Td	good	18	47	57	65	forest (dense trees); MacMillan: Td

For some classes, the assignment of curve numbers was very straightforward, as the classification systems overlap (e.g. *water* , bare soil *Gb*, and forest *Td*). Other classes needed a composed CN value. For instance, this was the case for all classes with grass/ crop *G&C* or agroforestry *tG&tC*. Also the *earth terraces* got a CN_2 composite. Theses stabilization infrastructures are formed by big terraces (about 5 m high) and have poor vegetation cover. Their CN_2 was therefore a combination of fair (extensive) grassland Ge(f) and contoured and terraced cropland with poor cover Ca(p,cont,terr.).

4.2.4.3 Hydrologic Response Unit

Hydrologic response units (HRU) are spatial units within a watershed that have similar properties and therefore react similarly to rainfall (Kalcic et al. 2015). In this thesis, the delineation of the HRUs corresponds to the object-images created in eCognition. In total there were 42'510 HRUs (or object-images). With the *Zonal Statistic Tool* in ArcMap the dominant HSG and mean slope (see Fig. 4.5) were defined for each HRU. The LULC (current) was already attributed to all of them due to the LULC mapping with OBIA. The attribute table was then exported to excel and saved as five separate copies, each representing one LULC or AMC scenario. The LULC was adapted to the corresponding scenarios, CN_2 was adjusted to the mean slope and, for scenarios $LULC_{wet}$ and $LULC_{dry}$, $CN_{1\alpha}$ and $CN_{3\alpha}$ were computed.

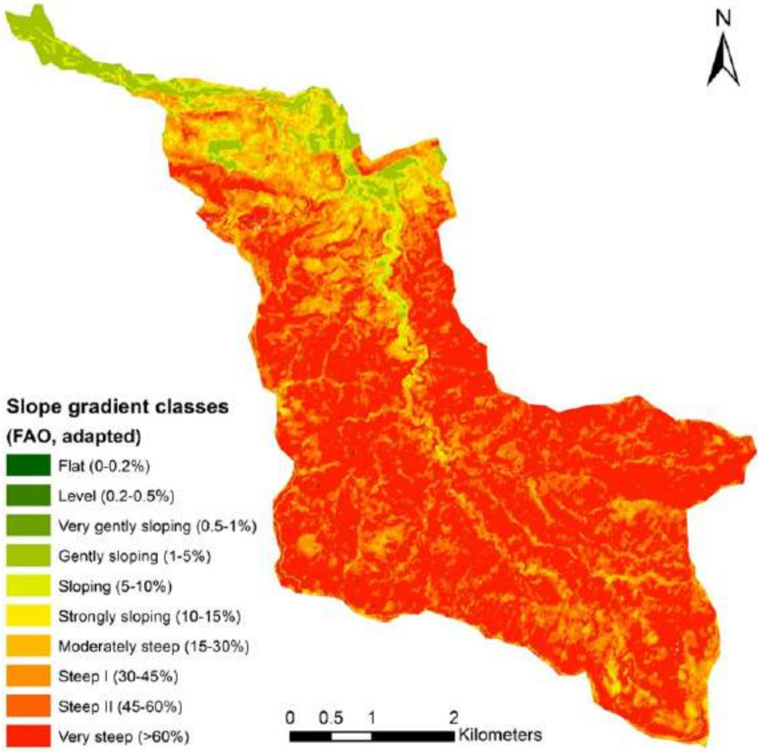

Figure 4.5: Slope map with mean slope for each hydrologic response unit (HRU)

4.2.4.4 Runoff calculation

All five scenarios were then tested under different rainfall events P [mm] (see Tab. 4.2). First, it had to be verified if the initial abstraction is met and runoff is generated. Considering the Equations (4.7), (4.8), and (4.9), this results in

$$P > \frac{0.2 \times 25400}{CN} - 254 \tag{4.12}$$

where I_a is given as a function of CN. If Equation (4.12) is false and rainfall P [mm] is less or equal to the initial abstraction I_a [mm], rainfall can be totally absorbed and no runoff is produced. If Equation (4.12) is true and rainfall is greater than the initial abstraction, runoff Q [mm] can be derived of

$$Q = \frac{(P - (\frac{0.2 \times 25400}{CN} - 254))^2}{P + (\frac{0.8 \times 25400}{CN} - 254)} \tag{4.13}$$

This was done for each HRU and then summed up in order to get the potential runoff contribution for the whole watershed for each $LULC$ and AMC scenario under different rainfall events.

4.2.4.5 Identifying hotspot areas

Based on the results of the potential runoff contribution, two different hotspots of land management and runoff contribution were identified. First, the LULC areas with highest runoff potential were located. This was done by calculating the percentage of rainfall being converted to runoff for each HRU under different rainfall events. Second, the LULC areas contributing the most to the total watershed runoff were identified.

4.2.5 Scenarios of land management change and their potential to reduce or increase runoff

In order to assess the potential of improved land management on runoff, additional scenarios were created based on soil cover; treatment and hydrologic condition (see Tab. 4.7). For those scenarios, too, curve numbers were assigned to each LULC class, the potential runoff for each HRU and the total watershed was calculated and subsequently, the hotspot areas with highest runoff potential and runoff contribution were identified.

Table 4.7: Specifications for the current land use and land cover (LULC) ($LULC_{avrg}$) as well as the worsened ($LULC_{poor}$) and the two improved ($LULC_{vetiver}$ with vetiver terraces and $LULC_{AF}$ with agroforestry systems) LULC scenarios. All four scenarios were done based on an average antecedent soil moisture condition (AMC)

Name	LULC	AMC
$LULC_{avrg}$	current	II
$LULC_{vetiver}$	improved with vetiver terraces	II
$LULC_{AF}$	improved with agroforestry	II
$LULC_{poor}$	worsened	II

Based on the original map with the current LULC ($LULC_{avrg}$), the $LULC_{vetiver}$ scenario was created by implementing vetiver terraces on all LULC classes with poor or sparse grass/ crop cover (Gb, Gs/Cs, tGs/tCs, TGs/TCs) as well as on the areas with annual and perennial crops (G/C and Cp, respectively). The $LULC_{AF}$ scenario was taken one step further. Since the Swiss Red Cross combines vetiver terracing with afforestation (see Chap. 5.1.1), $LULC_{AF}$ represents a future scenario, where the tree seedlings planted in $LULC_{vetiver}$ have grown to agroforestry systems (see Tab. 4.8). Conversely, for the $LULC_{poor}$ scenario with worsened land management, sparse grass/ crop became bare soil and good condition became poor. Additionally, deforestation was made more severe.

Please see Appendix 6.3 for tables with the LULC classes and the corresponding CN used for the different LULC scenarios.

Table 4.8: Changing Land use and land cover (LULC) classes for the scenarios with improved land management (classes, which did not change, are not shown): for $LULC_{vetiver}$ cultivated areas and sparse vegetation of current LULC ($LULC_{avrg}$) were improved with vetiver terraces; for $LULC_{AF}$ (more distant future) the trees planted together with vetiver grass have grown into agroforestry systems. Gb=bare soil, Gs/Cs=sparse grass/crop, G/C=grass/crop, TGs/TCs=dense agroforestry with sparse grass/crop, tGs/tCs=agroforestry with sparse grass/crop, Cp= perennial crop, G/Ct=terraced grass/crop, TCt=dense agroforestry with terraced crop, tCt=agroforestry with terraced crop, Cpt=terraced perennial crop, tCpt=agroforestry with terraced perennial crop

<table>
<tr><th>present
$LULC_{avrg}$</th><th>future I
$LULC_{vetiver}$</th><th>future II
$LULC_{AF}$</th></tr>
<tr><td>Gb</td><td rowspan="3">G/Ct</td><td rowspan="4">TCt</td></tr>
<tr><td>Gs/Cs</td></tr>
<tr><td>G/C</td></tr>
<tr><td>TGs/TCs</td><td>TCt</td></tr>
<tr><td>tGs/tCs</td><td>tCt</td><td>tCt</td></tr>
<tr><td>Cp</td><td>Cpt</td><td>tCpt</td></tr>
</table>

Table 4.9: Changing Land use and land cover (LULC) classes for the scenarios with worsened land management (classes, which did not change, are not shown): good vegetation cover was converted to sparse cover and deforestation was intensified. Td=Forest, TG/TC=dense agroforestry, TGs/TCs=dense agroforestry with sparse grass/crop, tG/tC=agroforestry, tGs/tCs=agroforestry with sparse grass/crop, Gb=bare soil, Gs/Cs=sparse grass/crop, G/C=grass/crop

<table>
<tr><th>current LULC
$LULC_{avrg}$</th><th>worsened LULC
$LULC_{poor}$</th></tr>
<tr><td>Td</td><td>TG/TC</td></tr>
<tr><td>TG/TC</td><td>tGs/tCs</td></tr>
<tr><td>tG/tC</td><td rowspan="2">Gs/Cs</td></tr>
<tr><td>G/C</td></tr>
<tr><td>Gs/Cs</td><td>Gb</td></tr>
</table>

Chapter 5

Results and Discussion

In this chapter, the main results of the thesis are presented and discussed. First, the findings of comparison of the land use practices are presented and discussed (5.1). This is followed by the presentation of land use and land cover (LULC) map resulted from the object-based image analysis (OBIA) and the discussion of its accuracy (5.2.1). Afterwards, the impact of land use and land cover on potential runoff contribution is presented and discussed (5.3).

5.1 Comparing the impacts of sustainable and conventional land use practices

This section provides the results and discussion of the comparison of the selected sustainable land management (SLM) and conventional land management (CLM) technologies. The analysis is based on the data obtained from the WOCAT questionnaires on SLM technologies (QT) and climate change adaptation (QCCA) and applies the methodological approach of Schwilch et al. (2014) and Giger et al. (2015). It compiles system knowledge about the processes of human-environment-relationships by comparing different land use practices within the study area.

5.1.1 Characterization of the selected SLM/ CLM technologies

For illustration, all five practices are shortly described in Boxes 1-5. Afterwards, the natural and human environment, as well as the main purpose and strength from land user's point of view, are described (see Tab. 5.1 and 5.2 respectively).

Natural environment All five technologies are applied on cropland except for agroforestry, which is a mixed land use practice. All of them are rain fed and adapted to a sub-humid agro-climatic zone with an annual rainfall of 1000-1500 mm. Soil depth is usually shallow (<50cm) to very shallow (0-20cm) and topsoil organic matter is rather low. Again, this does not apply to agroforestry, where soils are moderately deep and rich in topsoil organic matter. All five technologies are applied on steep to very steep slopes (31-60%).

Box 1 Weeded/ ploughed crop (short: conventional land management (CLM))

Figure 5.1: The technology of weeded/ ploughed crop (fren.: *culture sarclée*) represents the conventional land management in the Cormier watershed. It is a widely spread land management practice in the Mornes of Léogâne. As its name suggests, the technology's goal is to get rid of weeds. Since the land users do not have access to chemicals, they are forced to do it by ploughing the soil. They also have no access to mechanization, and even for animals, some slopes are too steep. Therefore, the soil preparation is done manually. First, they loosen the soil with the hoe or pickaxe and in a second step, they do ridges or terraces (depending on the slope) following the contour lines. This is not an SLM practice. After ploughing, the soil is loose and has no vegetation cover; hence, is very vulnerable to erosion. Nevertheless, the practice is widespread because the requisite know-how is available and it is easy to implement. Once established, it needs little maintenance. In Léogâne, pigeon peas, sweet potatoes, maize, beans and peanuts are commonly cultivated with this technology. (Photo: HP. Liniger 2017)

Box 2 Agro-silvo-pastoralist systems (short: agroforestry)

Figure 5.2: Agroforestry is a sustainable and traditional land use system. Earlier, when Haiti was covered with trees, agroforestry was a widespread land use practice. Today agroforestry can be found around houses and on the less sunny and more humid north-west facing slopes. These are usually agro-silvo-pastoralism systems, a combination of agriculture, forestry and pasturage of animals: land users take their cattle to these forests, attach them to a tree and feed them old banana trees. The cattle's dung fertilizes the area where it was kept attached. Afterwards, the land user can plant new crop/ trees on this spot. This land use practice is appreciated because it provides food throughout the whole year and offers an excellent environment to plant the cash crops cocoa and coffee. This land use practice also conserves biodiversity and protects downstream areas from landslides and rainwater runoff. However, the implementation of the agroforestry is very time-consuming; it may take several months or even years before one can harvest for the first time. (Photo: J. Eichenberger 2017)

Box 3 Progressive bench terraces with vetiver stripes systems and trees (short: vetiver terraces)

Figure 5.3: Progressive bench terraces formed by vetiver stripes and trees are an SLM technique for crop cultivation on slopes. The objective of this technology is to reduce soil loss and runoff velocity by reshaping the slope. The progressive bench terraces are formed by the successive deposit of sediments behind an anti-erosive structure. Vetiver grass is well suited as an anti-erosive structure since it has deep roots and it is readily available in Haiti due to the fragrance industry. The grass cannot be used to feed livestock. It can, however, be cut and used for mulching. The vetiver grass stripes are planted along the contour. The distance between the stripes depends on the slope gradient. Below (downstream) the stripes trees are planted to ensure a long-term slope stabilisation. Above, where the benches are formed, crops can be cultivated. This technique is not popular among small-scale farmers since they fear that the stripes make their arable land smaller. In Léogâne, this technology is used to restore degraded slopes. Ideally, it would be applied as a preventive measure against soil erosion. (Photo: left H. Liniger 2017, right J.Eichenberger 2017)

Box 4 Terra Preta raised garden beds (short: Terra Preta gardens)

Figure 5.4: Terra Preta raised garden beds are a combination of techniques from permaculture and the production of Terra Preta, an anthrosol. These garden beds are created with local resources: organic material (i.e. ligneous material, dry or fresh straw or harvest residues), charcoal powder and ashes or other fertile materials. These raised garden beds are highly fertile and enable a higher yield compared to the CLM. Moreover, when put in place on sloping terrain, the garden beds slow down erosion strongly and can therefore protect houses downstream. The limiting factor of this technology is its complex implementation which generally requires a certain level of support by technicians.(Photo: J. Eichenberger 2017)

Box 5 Wattle fences for gully reduction (short: wattle fences)

Figure 5.5: Wattle fences for gully reduction are a bioengineering technology and also an SLM technology. The stakes of the fences are made of regrowing material (e.g. *Moringa oleifera* or *Spondias mombin*); over time, they will take roots and stabilise the fence. By weaving thin branches or slats (e.g. bamboo cut lengthwise) between the upright stakes the wattle is formed. This woven lattice serves as a catch basin for sediments and organic material coming from upstream. The accumulated soil is very fertile and may be used to plant crops with high nutrition requirements as bananas, for instance. In the long-term, the stakes produce plant material, which the land users can cut and eat or sell. Moringa, for instance, is rich in protein, calcium, potassium, iron, vitamin C and is being promoted by the Haitian Government to address the country's chronic malnutrition. Because of its multiple purposes, this SLM technique is well accepted by the land users. In combination with other SLM technologies (i.e. progressive bench terraces or afforestation), wattle fences contribute to watershed protection. (Photo: J. Eichenberger 2017)

Table 5.1: Natural and human environment of the sustainable and conventional land management

	Wattle fences	**Terra Preta gardens**	**Vetiver terraces**	**Agroforestry**	**CLM**
Natural Environment					
Soil texture (topsoil)	coarse - medium	medium - fine	coarse - medium	medium - fine	coarse - medium
Soil texture (>20cm below surface)	coarse - medium	coarse - medium	coarse - medium	medium - fine	coarse - medium
Soil depth	(very) shallow <50cm	(very) shallow <50cm	(very) shallow <50cm	moderately deep (51-80cm)	(very) shallow <50cm
Topsoil organic matter	low	low	low	high	low
Slope	steep very steep	steep very steep	hilly - steep	steep very steep	hilly - steep
Human Environment					
Applied on	small-scale	small-scale	small-/ medium-scale	medium-scale	small-scale
Wealth level	very poor	very poor	poor	poor - average	poor
Individuals/ households or groups/ community	both	Individuals/ households	groupes/ community	both	Individuals/ households
Access to services and infrastructure	poor (except market)	poor (except market)	poor (except market)	poor (except market and water)	poor (except market)
Off-farm income	<10%	<10%	<10%	<10%	<10%

Human environment Wattle fences, Terra Preta gardens and CLM are mainly applied on small-scale land holdings (wattle fences also by groups/ community), vetiver terraces and agroforestry instead on medium-scale. The land users' relative level of wealth ranges from very poor to poor, land users with agroforestry have an average level of wealth compared to local standards. Remoteness and marginality are essential factors as most sites have relatively difficult access to several services and infrastructures as health, education, or roads. Drinking water and sanitation are poorly accessible except for land users with agroforestry. The access to the market, however, is moderate for all five cases. Most of the land users in the area are both self-subsistent and market-oriented. Agriculture is their primary income; less than 10% depend on off-farm activities.

Main purpose and strength from land user's point of view All five practices have multiple purposes. All four SLM technologies' main purpose is to reduce/ prevent/ restore land degradation and reduce disaster risk. Except for Terra Preta gardens, all SLM technologies aim to protect the watershed and downstream areas. Terra Preta is a very local small-scale intervention, which cannot protect a sufficiently large area to have a downstream impact. Additionally, all SLM technologies but the wattle fences adapt to or mitigate climate change and its impacts, and aim to improve agricultural production. The latter also applies to CLM. This is also reflected in the technologies strengths from the land users' point of view (according to Jean Cars Dessin, SLM specialist of the Haitian SRC staff): *increase of arable area*, *increase in yield*, *production throughout the year* and *fast production* are just some of the advantages mentioned concerning improved crop production. For wattle fences and vetiver terraces, the environmental consciousness plays an important role, too: the land users are aware of the technology's benefits such as gully correction and soil retention. Economic benefits in the form of cash crops are stated as strengths of agroforestry (e.g. cocoa and coffee) and wattle fences (plant material from stakes, e.g. moringa). The key motivation for applying CLM is that the know-how is readily available and the implementation is straightforward.

The examination of the natural and human environment in which the technologies are applied highlights the unfavourable conditions that are typical for the Mornes of Léogâne. All the technologies are adapted to the steep topography, where soil erosion by water is the main degradation problem that must be tackled. Nevertheless, they all are applied on less steep slopes or even flat topography as well. In the WOCAT QT, however, it is only possible to indicate the average slope. The human environment presented in Table 5.1 may be considered representative of average land users within the Mornes. The difference in wealth levels between land users applying wattle fences and Terra Preta and those with Vetiver terraces and CLM may be traced back to the fact that different people compiled the data. Regardless of using local or international standards, most of these small-scale farmers are considered to live in poverty. Regarding the scale of the technologies, vetiver terraces are considered to be medium-scale. However, their land-users are small-scale farmers. In order to implement the terraces, they have to merge their lands since this SLM technology only takes its full effect when applied on the whole slope. The wattle fence technology is the only one which does not aim to improve production since its main purpose is to reduce land degradation, protect watershed and reduce disaster risk. Nevertheless, fertile soil is formed behind the fences which improves production and the land users may also benefit from the plant material (e.g. if the stakes are made of

Table 5.2: Technologies' main purpose and strength from land user's point of view (accroding to Jean Cars Dessin, SLM specialist of the Haitian SRC staff)

	Wattle fences	**Terra Preta gardens**	**Vetiver terraces**	**Agroforestry**	**CLM**
Main Purpose					
Improve production		X	X	X	X
Reduce, prevent, restore degraded land	X	X	X	X	
Conserve ecosystem				X	
Protect watershed and downstream areas	X		X	X	
Preserve/ improve biodiversity				X	
Reduce risk of disasters	X	X	X	X	
Adapt to/ mitigate climate change and its impacts		X	X	X	
Create beneficial economic impact		X		X	
Create beneficial social impact		X			
others: adapt to the slope steepness			X		X
Technologies' strengths	more arable area	strong increase in yield	mulching material	production throughout the year	fast production
	gully reduction	improved production production quality	soil/ sediment retention	diversity of products	knowhow available
	cash crop (from moringa stakes)	shortened crop cycle	soil humidity	cash crops (coffee, cocoa)	easy implementable

moringa).

5.1.2 Impacts of SLM and CLM on water cycle

The concept of green water use efficiency (GWUE) was used to assess if the technologies do minimize unproductive water loss while they maximize the productive flow of water. Therefore, the values (-3 to 3) assigned to the impacts in documentation of the practice were added together for each practice separately. For a measurable improvement, a combined value of four or more points had to be reached, in doing so the impact was high and/ or affected two or more indicators.

Three SLM technologies appeared to produce measurable improvements in GWUE (see Tab. 5.3): Terra Preta gardens scored 5, vetiver terraces 7, and agroforestry 10 out of 12 points. The wattle fences reached a value of 3 and the CLM practice -12 points. The latter has a very negative impact on all four indicators and therefore clearly worsens the GWUE. A key cause of water loss is surface runoff (Schwilch et al. 2014). All four SLM technologies assessed reduce runoff. Soil moisture is improved with all documented SLM technologies.

Schwilch et al. (2014) state that cross-slope barriers are very effective in increasing GWUE. This can be affirmed considering the value of 7 points reached by the vetiver terrace technology. The wattle fences reached a value of 3 because it does not necessarily improve soil cover, and it does not reduce soil evaporation. Bier (2016) estimated that its impact on runoff reduction is rather small

Table 5.3: Green Water Use Efficiency (GWUE) of the land use practices

	Wattle fences	Terra Preta gardens	Vetiver terraces	Agroforestry	CLM
Increased soil moisture	2	3	2	3	-3
Reduced surface runoff	1	2	2	3	-3
Improved soil cover	0*	0*	2	3	-3
Reduced soil evaporation	0*	0*	1	2	-3
GWUE	**3**	**5**	**7**	**11**	**-12**

* There was no value on soil cover and evaporation documented for wattle fences and Terra Preta gardens. In order to be able to calculate a value for the GWUE, the assessed impact in the documentation was converted into a value: the value 0 was set for neutral impact, - 3 for a very negative and +3 for a very positive impact.

(reduction of 5-20%). This is because they are only applied to specific points. However, according to is gully-correction-function, it can be assumed that the runoff accumulated in the gullies is slowed down due to these "obstacles" and, hence, loses its destructive force.

Although only three of four SLM technologies show measurable improvement of the GWUE, it should be noted that all four technologies display some positive impact on GWUE and all of them perform distinctly better than the CLM practice.

5.1.3 Impacts of SLM and CLM on soil degradation

The three SLM technologies vetiver terraces, agroforestry, and wattle fences have a very positive impact on soil loss reduction (see Fig. 5.6). It is estimated that they decrease soil loss by 50-100%. For the Terra Preta gardens, no impact was documented. Therefore, it is assumed that its impact is negligible. Concerning soil accumulation, vetiver terraces and Wattle fences show the best results. Moreover, Terra Preta gardens are reported to improve soil accumulation. As illustrated in Figure 5.6, CLM increases soil loss and hinders soil accumulation at the same time.

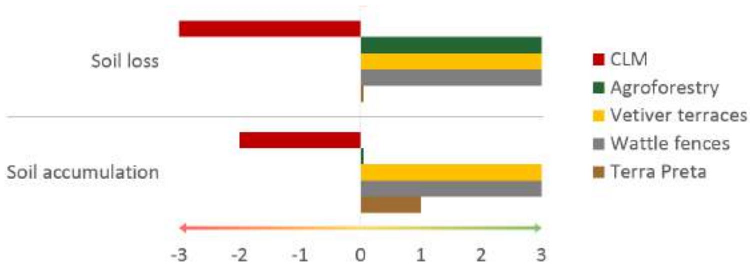

Figure 5.6: Soil loss and soil accumulation (-3 = very negative impact (-50-100%), -2 = negative impact (-20-50%), -1 = slightly negative impact (-5-20%), 0 = negligible impact, 1 = slightly positive impact (+5-20%), 2 = positive impact (+20-50%), 3 = very positive impact (+50-100%))

From Table 5.4, it can be seen that all four SLM technologies aim to combat soil erosion by water, particularly gully erosion. All besides wattle fences are used against surface soil erosion. Off-site degradation effects are addressed, especially by vetiver terraces and agroforestry. Additionally, to soil erosion by water, Terra Preta gardens and, notably, agroforestry also combat biological degradation. Agroforestry and vetiver terraces are effective against the same types of water degradation. From all four SLM technologies, agroforestry addresses the most degradation types, followed by vetiver terraces. The CLM does not combat a single degradation type but causes several of them.

The positive impact of vetiver stripes and wattle fences against soil loss are illustrated in Figures 5.3 and 5.5. The photographs were taken during the field trips in autumn 2017. Figure 5.3 shows the accumulation of sediments behind a recently implemented vetiver stripes. Figure 5.5 shows lots of organic material accumulated upstream of the wattle fence. In both cases, most of this fertile soil would have been washed away if it were not for these structures.

For the Terra Preta gardens, no impact on soil loss was documented although soil erosion by water (surface and gully erosion) is one of the degradation problems addressed by this SLM technology. Soil erosion by wind, chemical soil deterioration, and physical soil deterioration are not addressed by any of these SLM technologies. This may be explained by the fact that soil erosion by water is such a prominent and top priority degradation threat that the others are not perceived. Physical soil deterioration by sealing and crusting and compaction is surely a problem that is heavily linked with soil erosion. Soil chemical deterioration on heavily eroded land is surely also an issue as soil organic matter is being lost and nutrients are lost and washed out during heavy rainfall events.

5.1.4 Impacts of SLM and CLM on diversification and enhancement of crop production

The results for crop diversification and enhancement are compiled in Figure 5.7. CLM scores poorest by far. Agroforestry has a positive impact on all except for production area, where its impact is

Table 5.4: Degradation types addressed by the sustainable land management technologies and caused by the conventional land management practice

	Wattle fences	**Terra Preta**	**Vetiver terraces**	**Agroforestry**	**CLM**
Soil erosion by water	addresses: gully erosion/gullying, riverbank erosion	addresses: loss of topsoil/surface erosion, gully erosion/ gullying	addresses: loss of topsoil/surface erosion, gully erosion/gullying, mass movements/ landslides, off-site degradation effects	addresses: loss of topsoil/surface erosion, gully erosion/gullying, mass movements/ landslides, off-site degradation effects	causes: loss of topsoil/surface erosion, gully erosion/gullying, off-site degradation effects
Water degradation	–	–	addresses: aridification, change in quantity of surface water, change in groundwater/aquifer level, decline of surface water quality	addresses: aridification, change in quantity of surface water, change in groundwater/aquifer level, decline of surface water quality	causes: aridification, change in quantity of surface water, change in groundwater/aquifer level
Biological degradation	–	–	–	addresses: reduction of vegetation cover, loss of habitats, quantity/biomass decline, quality and species composition/ diversity decline, loss of soil life	causes: reduction of vegetation cover, loss of habitats, quantity/biomass decline, quality and species composition/ diversity decline, loss of soil life

considered negligible. Vetiver terraces show a slight improvement in crop production, crop quality and farm income. Its impacts on the risk of crop production failure, crop diversity and production area are negligible. The Terra Preta gardens have the most significant impact on crop productivity, crop diversity and production area. The high productivity of the Terra Preta gardens is illustrated in Figure 5.8. The photographs were taken at the beginning and the end of the field trip in 2017. Only five and a half weeks after its implementation the land user was able to harvest the first spinach leaves. With Terra Preta garden beds, crop diversity is enhanced moderately. Its impact on the risk of crop failure and farm income is negligible. Since Terra Preta gardens are mainly used for subsistence farming, farm income is not impacted. Wattle fences, however, have a slight positive impact on farm income due to the sale of plant material gained from the regrowing stakes (see Box 5). It also has a slightly positive impact on crop production, since the production area is increased. The impacts on crop quality, risk of crop failure or crop diversity, however, were not documented.

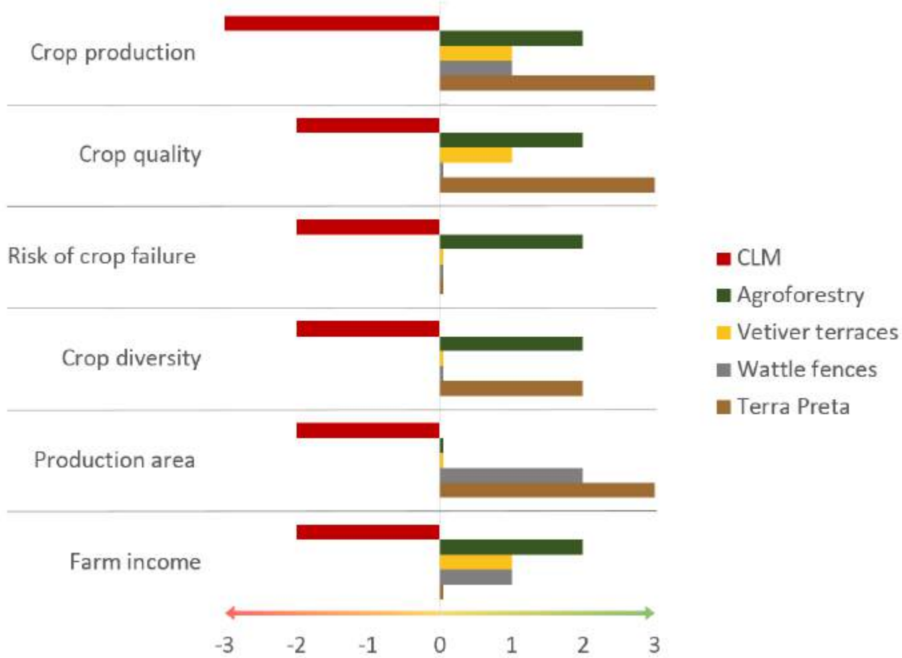

Figure 5.7: Diversified and enhanced crop production (-3 = -50-100%, -2 = -20-50%, -1 = -5-20%, 0 = negligible impact, 1 = +5-20%, 2 = +20-50%, 3 = +50-100%)

Figure 5.8: Left: Implementation of a Terra Preta raised garden bed at the end of September 2017; right: 6 weeks later the spinach is ready for harvest

According to Jean Carls Dessin (the DRR specialist of the local SRC team), the very negative impact of the CLM is especially true in the long-term. Conversely, in the short-term, CLM may even have a less negative or even neutral impact. Also, the impacts of vetiver terraces have to be separated into long- and short-term impacts: the vetiver terraces' improvements on crop diversity and enhancement are only achieved in the long run. Since the technology is often applied on heavily degraded soils, it takes a while to improve crop production. Moreover, vetiver terraces only have a slightly positive impact on crop production because vetiver grass is not consumed by human nor is very palatable to livestock. There are some progressive terraces with sugar cane instead of vetiver grass stripes. According to Jean Carls Dessin, this technology would improve crop production a lot. However, since vetiver grass is by far better adapted to dry periods, the SRC team in Léoâne chose to promote progressive terraces with vetiver grass, since the technology's primary purpose is to stabilize slopes in order to enable a more sustainable crop production than the CLM technology. The Terra Preta gardens' risk of crop failure may be lower than documented in WOCAT. Typically, these garden beds are close to the land users' house, and actions against crop failure are easier to take. If, for instance, the rainy period starts later than expected, it would be easy to irrigate these garden beds.

5.1.5 SLM and CLM technologies and their socio-cultural benefits

Food security/ self-sufficiency is improved by all SLM technologies and decreased by the CLM practice. Terra Preta gardens are able to increase it by 50-100% and agroforestry by 20-50%. The knowledge on SLM and land degradation is increased for vetiver terraces and wattle fences. For the other tree technologies, no significant impact was documented.

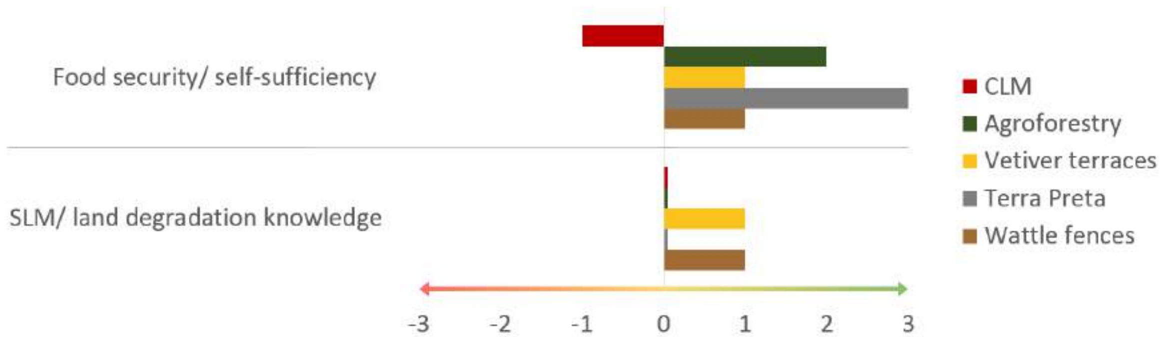

Figure 5.9: Socio-cultural Benefits (-3 = -50-100%, -2 = -20-50%, -1 = -5-20%, 0 = negligible impact or n.a., 1 = +5-20%, 2 = +20-50%, 3 = +50-100%)

The fact that agroforestry and Terra Preta gardens scored well regarding the improvement of food security/ self-sufficiency may be explained by their high crop diversity and the low risk of crop failure (see Chap. 5.1.4). The improved knowledge on SLM and land degradation of land users applying wattle fences and vetiver terraces can be traced to the fact that the SRC team assists in their implementation. The SRC does not pay the land users for working. Therefore, a lot of sensitization work on the benefits of the SLM technologies has to be done in order to motivate the land users to make an effort and apply the respective technologies. The SRC team also assists in the implementation of the Terra Preta gardens. In this case, however, the land users might be motivated by the improvement in food security and not by its environmental benefits. For CLM and agroforestry, no significant impact on the knowledge on SLM and land degradation was documented, but this does not mean that there is no knowledge available. In fact, when speaking to land users with agroforestry systems, it was observed that they are aware of its multiple benefits. However, both CLM and agroforestry are traditional land use practices, and therefore, there has not necessarily been any change in the land users knowledge on SLM and land degradation.

5.1.6 Resilience towards climate change and variability

According to the information compiled with the WOCAT Climate Change Adaptation Questionnaire (QCCA), the study area is exposed to following climate change and climate-related extremes (disasters):

Climate change According to land users and SLM experts statements, seasonal rainfall patterns are changing in the Cormier watershed. The smaller rainy season seams to get delayed on the onset. About one or two decades ago, the first rainy period began in early March and ended end of May. In the last few years, however, it tended to start only by mid-April and lasted until mid-June. This means that the dry season gets longer and this first rainy season a bit shorter. According to the people living in the area, the rainfall amount seems not to have changed. Yet, they observed heavier rainfall in May and June.

Climate-related extremes People observed an increase in frequency and intensity of *tropical storms* in the past few years/ decades. In addition, there have been *extra-tropical storms* also in December whereas the hurricane season officially ends in November. As mentioned above, *local rainstorms* have increased in frequency and intensity in May and June. As for hydrological disasters, floods are becoming more and more frequent and intense as well, especially during the rainy and hurricane season. According to local land users, the river floods whenever it rains. On the other hand, droughts became more frequent and severe during the dry season of December to February as well as in March, since the seasonal rainfall tends to be delayed. Moreover, insect and worm infestation became more intense during this dry season. These findings coincide with the climate change predictions presented in Chapter 2.2.1.

In the following, the findings of the WOCAT Questionnaires on SLM Technologies and on Climate Change Adaptation are presented and discussed for the climate-related threats mentioned in the documentations: drought and delayed seasonal rainfall, and torrential rain and tropical storm. The two technologies Terra Preta gardens and wattle fences were not documented with the WOCAT Climate Change Adaptation Questionnaire, but with the WOCAT Questionnaire on SLM Technologies only.

5.1.6.1 Torrential rain and tropical storm

Terra Preta gardens are not very vulnerable to heavy rainfalls and storms. The gardens are often found close to the houses and therefore, usually protected by the trees of agroforestry systems. Also wattle fences resists these extreme events. This technology actually need heavy rains to fulfil its purpose of slowing down runoff and holding back soil and organic material. Vetiver terraces are resilient to rain storms, too. Rainwater is hold back in the channels behind (upstream) the grass stripes. On the one hand, this enables rainwater to infiltrate and to recharge the springs. On the other hand, the vetiver stripes and the progressively formed terraces slows down the runoff and reduce downstream flooding and siltation. Moreover, the deep roots of vetiver grass reduce soil erosion by water and stabilize slopes. Nevertheless, there is much of clearing work to do after a strong storm (e.g. replanted grass strips if damaged by runoff). Also the food security and self-sufficiency on vetiver terraces may decrease strongly, especially with strong winds. Costs and income of land users with vetiver terraces are impacted by tropical storms and local rainstorms because of crop failure (e.g. cash crop), new seeds that have to be bought (if there is still time to plant in this same planting season) and working hours spend with clearing work. Severe tropical storms also impact agroforestry systems. They decrease crop production, hence, increase the risk of crop failure. Heavy winds may damage the vegetation cover severely. Also here income and costs may be affected: cocoa and coffee, for instance, are cash crops cultivated in agroforestry systems. Also the clearing work load increases depending on the intensity of the event. Additionally, the diversity of income sources may decreases slightly. Compared to the other technologies, agroforestry performs the best regarding torrential rains and tropical storms. In the Cormier watershed, many houses have agroforestry systems around them, amongst others, for protection reasons. The trees absorb the energy of the wind. And although the winds strip the trees by breaking the branches and blowing away the leaves, after one year, most trees start to recover again. Other DRR benefits of agroforestry systems regarding heavy rains and storms are strongly reduced and slowed down runoff, hence, lower flood risks downstream as well as a strong decrease of the risk of landslides and debris flows. For CLM, however, these climate-related extremes are disastrous in every aspect of crop production. Tropical storms and local rainstorms have a very negative impact on costs and income of land users with CLM because of crop failure (e.g. cash crop), new seeds that have to be bought (if there is still time to plant in this same planting season) and working hours spend with clearing work. After a storm, the work load is high. The ridges made of lose soil are very vulnerable to rainfall and have to be rebuilt. On areas with CLM, such extreme events severely increase surface runoff, soil loss, risk of land slides and downstream flooding and siltation. This may cause severe damages on neighbour's fields and public infrastructure. The increased runoff decreases (spring) water quality drastically. This is a concern for all technologies, but especially for CLM areas because of the high runoff potential. This aggravates the health situation after an extreme event. The water can, however, be used for animals. Moreover, agroforestry systems and vetiver terraces promote the infiltration of rainwater. This is not the case for CLM: the technology increases the runoff and the groundwater table is not recharged. Additionally, increasing tropical storms and local rainstorms aggravate the situation of socially and economically disadvantaged groups. Here again, especially the land users practising CLM are affected. Land users having larger agroforestry systems are usually wealthier than those practising CLM (see Tab. 5.1).

Droughts and delayed seasonal rainfall Terra preta reduces drought impacts by increasing food security. Although they are normally rainfed, it would be possible to irrigate the gardenbeds during persistent dry periods since it is a small-scale technology and they usually are located close to the house. The impacts of drought and delayed seasonal rainfall on wattle fences were not documented. It can, however, be assumed that its vulnerability primarily depends on the vegetal material which it is made of. Moringa and bamboo, for example should be able to resist to drier periods. Moreover, the soil and organic material behind the fence might be able to store soil moisture over a longer period. Delayed seasonal rainfall can, however, be very harmful to vetiver terraces in the first three month after their implementation. The vetiver cuttings are planted with the start of the first rainy season and they are very vulnerable to delayed seasonal rainfall. However, once it has been able to create deep roots, the vetiver grass is very drought resistant. The soil behind the grass stripes remains longer moist because of the infiltrated rainwater. And once the vetiver has grown well, the land users may cut the grass and use it as mulch. This slows down the evaporation of water and keeps moisture in the soil. Nevertheless, during severe droughts, groundwater table/ aquifer and soil moisture decrease moderately up to severely. In such situations even vetiver terraces cannot impede crop failure. However, in Léogâne the Swiss Red Cross combines the vetiver terracing with reforestation. In the long run, it is likely that the grown trees will promote a microclimate which will make the technology more resilient towards droughts and delayed seasonal rainfalls. With climate change land users also experienced an increase in insect/ worm infestation, especially during the dry season (usually Dec-Feb and with delayed seasonal rainfall in March, too). This will lead to an increase in pest/ diseases and harmful species. However, beneficial species might increase slightly as well. Agroforestry is very resilient to droughts due to their microclimate. However, depending on the size of the agroforestry system, droughts may slightly increase the risk of crop failure by decreasing the crop production and crop diversity. Delayed seasonal rainfall, however, have almost no impact on the productivity of agroforestry systems. During severe droughts, however, water availability, groundwater table/ aquifer, and vegetation cover decrease slightly and soil moisture decreases moderately. Due to the more humid microclimate, insect/ worm infestations are no concern in agroforestry systems. On areas with CLM, drought has a very negative impact. It does not only severely increase the risk of crop failure but also reduces fodder production and quality. Unlike agroforestry systems and vetiver terraces (the latter only on the long term), CLM does not create a favourable microclimate, which makes the technology more resilient to drought. Also, in CLM areas, droughts have a very negative impact on expenses on agricultural inputs, farm income and diversity of income sources. The variability of seasonal rainfall affects the crop production as well. If the planted seeds do not get any rainwater at the beginning of the planting season, the risk of crop failure increases. Moreover, insect/ worm infestation coming along with droughts have a severe impact on crop production and quality and increase the risk of crop failure drastically. Combating insect and worm infestations increase the workload. However, also land users practising CLM have observed a slight increase in beneficial species during insect and worm infestations. Finally, delayed seasonal rainfall and droughts decrease water quantity, groundwater table/ aquifer and soil moisture severely.

Due to the CLM's high runoff and low infiltration rate, the recharge of the groundwater table is slow. Hence, during droughts, the water availability decreases severely. The water quality, however is not impacted.

These results show that all presented technologies are vulnerable to climate change and climate-related extremes. Nevertheless, the SLM technologies are much less vulnerable than the CLM. Agroforestry resulted in being the most resilient technology and the best practice for DRR and CCA. Vetiver terraces (when trees are not fully grown yet) and CLM are sensitive to the temporal variability of seasonal rainfall when it comes to crop production. Their vulnerability to crop failure might be attributed to the absence of a microclimate which buffers the impacts but also to their much lower crop diversity. Regarding heavy rainfalls, vetiver terraces and agroforestry perform much better than CLM. The deep roots stabilize the soil and reduce runoff and soil loss. Hence, damages by floods, siltation or land slides on neighbour's fields and public infrastructures are minimized. Moreover, due to improved infiltration, the groundwater table recharge is supported.

5.1.7 Economic benefits and costs of SLM technologies

As mentioned before, the cost-benefit analysis was done based on Giger et al. (2015). They analysed the observed costs, which include the *establishment* and *maintenance costs* (quantitative variables), and the *perceived cost/ benefit ratio* (qualitative variables). First, the results are presented, followed by a short discussion.

Observed costs of SLM and CLM technologies

In the QT, the costs were documented in Haitian Gourdes [HTG]. Therefore, in a first step, the cost had to be converted to US dollars [USD] using the then applicable exchange rate (also documented in the QT). In a second step, the costs were converted to US dollars per hectare [USD/ ha] (see appendix for conversion processes). Table 5.5 summarizes the establishment costs and maintenance costs of the different technologies. For the Wattle fences, no maintenance costs are documented because it hardly needs one. Since the establishment costs were documented for one unit of wattle fence, it does not seem reasonable to convert the costs to hectares.

Regarding the costs for one hectare [ha], Terra Preta gardens are by far the most expensive to establish and maintain, followed by vetiver terraces. Agroforestry and CLM are much cheaper than the other two practices. Agroforestry is cheapest for establishing and CLM for maintaining.

Different factors are affecting these costs. First, there is the technical support. In order to establish SLM technologies as vetiver terraces, wattle fences or home gardens, the Swiss Red Cross (SRC) offers technical support. For the latter two technologies, this skilled labour is by far the most expensive input. For vetiver terraces, the weather condition during the first three months after the implementation is crucial. If it rains too much, the runoff may break the bench terraces and wash the vetiver seedlings away. Usually 5% of the vetiver seedlings have to be replaced after heavy rains in the first three months. Damages due to drought in the first months after implementation are much more costly. Up to 40% of the vetiver seedlings have to be replaced. However, once the

Table 5.5: Establishment and maintenance inputs and costs US-Dollars (USD) for the sustainable and conventional land management technologies

	Wattle fences	Terra Preta gardens	Vetiver terraces	Agroforestry	CLM
Establishment costs per documented unit	35 USD/ Unit	40 USD/ 11 m^2	260 USD/ 200 m	80 USD/ 0.5 ha	205 USD/ 0.5 ha
Establishment costs [USD/ ha]	N.a.	39040	2610	160	360
Maintenance costs per documented unit	N.a.	60 USD/ 11 m^2	360 USD/ 200 m	190 USD/ 0.5 ha	50 USD/ 0.5 ha
Maintenance costs [USD/ ha y-1]	N.a.	61029	3610	390	100
Important factor affecting costs	technical support	labour and technical support	technical support and weather condition during the first 3 month	price of seeds/ seedlings and their economic life	

roots are deep enough, vetiver is very drought resistant grass type. Another crucial factor affecting the establishment and maintenance costs are the prices of the seeds and seedlings. On the one hand, the prices vary from species to species. Cacao and coffee seeds, for instance, are much more expensive than papaya seedlings or maize seeds. However, their economic life exceeds 20 years. Moreover, bananas are cheap and produce suckers, so they endure a more or less continuous supply of shoots. On the other hand, the price of the seeds and seedlings vary from season to season. During harvest time the prices are low. In March, when the planting season starts, they are high. If possible, land users store seeds from their own harvest, so they do not need to spend money on buying seeds for the next planting season.

Perceived cost/ benefit ratios

The perceived[1] short-term and long-term cost/ benefit ratios are shown in Table 5.10. The cost/ benefit ratio is perceived to be positive for all SLM technologies, both in the short and long term. This implies that SLM measures are considered to pay off after as little as 1-3 years. On the long run, the cost/ benefit ration for SLM technologies are even more positive; except for agroforestry, all SLM technologies are perceived to have a very positive ratio of benefits to costs. For the CLM technology, however, the ratios of benefits to costs are all negative except for the ratio of benefits to establishment costs in the short term. Especially in the long term, the CLM performs poorly: the perceived ratio of benefits to both establishment and maintenance costs of CLM are very negative.

Overall, the results suggest that land users perceive most SLM technologies as having benefits that justify the required investments. This shows, in line with previous research (see Giger et al. 2015), that economic motivation is a key factor in land users' decisions to adopt SLM technologies.

There are, however, some essential points, which deserve special attention. First, the observed costs should be treated with caution. For instance, the land users (the labourers), are not paid in a monetary way. In Léogâne, the land users are organized in *konbits*, land user groups of approximately ten people. These people help each other out on a regularly basis without getting paid or

[1]The WOCAT questionnaires on the land use practices were filled out with Jean Cars Dessin (SLM specialist of the Haitian SRC staff). The perceived cost/benefits represent the land users point of view that Jean Cars Dessin experiences in the field.

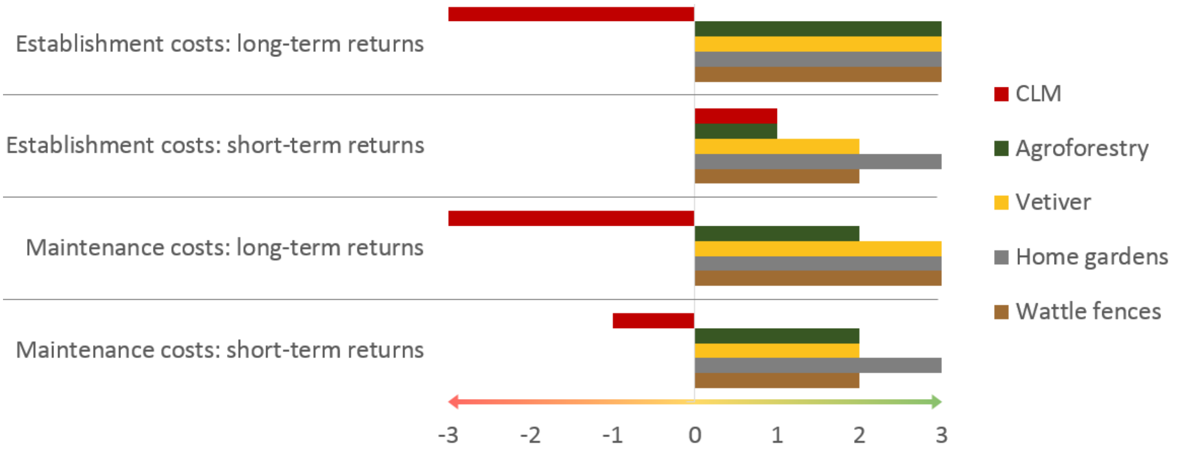

Figure 5.10: How do the benefits compare with the establishment and maintenance costs, respectively? (The WOCAT questionnaires on the land use practices were filled out with Jean Cars Dessin, SLM specialist of the Haitian SRC staff. The perceived cost/benefits represent the land users' point of view that Jean Cars Dessin experiences in the field.)

receiving any share of the harvest to which they contributed. They just get a coffee (occasionally also a hot meal) in return. Nevertheless, this labour was listed in WOCAT QT with the average daily wage of hired labour, since, in theory, they would have cost that much. Secondly, the establishment and maintenance costs of vetiver terraces analysed in this case do not include costs for crop seeds. It is possible to cultivate maize, beans, bananas and so forth, between the lines of vetiver. The SRC, however, recommends only to cultivate the terraces once the vetiver has grown roots, thus, only three to four months after the establishment of the technology. Thirdly, the question arises why the CLM is so popular even though its perceived cost/benefit ratio is mainly negative. According to the strengths of this practice in the land users' point of view (see Tab. 5.2, this technology is easily implementable, the know-how is available (no technical support needed) and it promotes fast crop production (does not need any adaptation time like the vetiver terraces). However, its negative impacts may have gotten worse during the past few years. Some decades ago, land users may have applied this technique only on gentle slopes. Now, Haiti went through a significant population growth during the last few decades (see Chap. 2.1) and, therefore, the pressure on land has increased severely. Marginalised land users are forced to cultivate steep slopes and have not yet adapted their techniques. Another possible explanation might be the severe poverty in Haiti. Most of the people in the study area are small-scale and (semi-)subsistence farmers. Less than 10% of the land user applying CLM have an off-farm income. They live from hand to mouth and do not necessarily have the luxury to wait for vetiver grasses to grow roots. As shown in Figure 5.10, CLM has a slightly positive cost/ benefit ratio in the short term. And not all crops are suitable for planting in agroforestry systems. Peanuts, beans and corn, for instance, need a lot of sunlight. As mentioned before, this is why they are planted on the sunnier southeast facing slopes.

5.1.8 Discussion

All the values (qualitative and quantitative) assessed with the WOCAT QT and QCCA are based on estimations and the opinion of the Haitian SRC SLM specialist, Jean Carls Dessin, and observations of the compilers of the data [2]. Nevertheless, the results show clearly that the CLM practice is not sustainable. It performs poorly in almost all aspects assessed; it has a very negative impact in green water use efficiency, aggravates soil loss, causes and/or accelerates several types of land/ water degradation, downgrades crop production on the long term and, hence, decreases food security. The only positive aspects are that in the short-term run, it slightly improves farm income and its perceived cost/ benefit ratio is slightly positive. So the question arises why this unsustainable land use practice is so popular. In the author's opinion, this can be explained by the fact that earlier when population pressure was no problem, land users practiced the CLM technology on flat or slightly sloping plots. In the last few decades, however, the population density rose drastically[3]). Hence, the pressure on land became strong and people started to deforest and cultivate steeper slopes. It can be assumed that due to the short time the technology was not adapted to the new circumstances, except for making terraces following the contour lines. In summary, CLM is widely spread because except for agroforestry no other SLM technology has been applied in the area for long enough to be socially accepted and institutionalized. During the field trip in 2017, there were few implemented vetiver terraces, however, none of them was used for crop production, although theoretically, the plots can already be used for cultivation tree month after the technology's establishment. Agroforestry system, however, would have the convincing potential for poor land users.

5.2 Land use and land cover map

5.2.1 Resulting land use and land cover map

Figure 5.11 shows the land use and land cover (LULC) map resulting from an object-based image analysis (OBIA) in eCognition. It provides the basis for analysing the impact of LULC on potential runoff contribution. The north-west/ south-east vegetation pattern is clearly visible (see also Fig. 5.15): On north-west facing slopes, there are especially classes with high tree percentages (forest *Td* or dense agroforestry *TG/TC*) whereas, on the south-east facing side of the watershed, there is rather sparse vegetation *Gs/Cs* or bare soil *Gb*. Perennial crops are predominantly located in the lower zone of the watershed. With 823 ha the category forest *Td* made up by far the largest share of the total watershed area (30%). The area shares of the other LULC classes are illustrated in Figure 5.12.

Table 5.6 shows the accuracy of the LULC map in the form of an error matrix with the user's[4] accuracy on the right and the producer's[5] accuracy in the second-last row. They vary between 0.45 - 1.00 and 0.47 - 1.00, respectively. As one might expect, the manually classified thematic layers (T.L., including: water, urban area, earth terraces and sand mines) showed the best values for user's

[2] K.H. Bieri for *Terra Preta raised garden beds*; H. Gambon for *wattle fence for gully correction*; and J. Eichenberger for *agro-silvo-pastoralist systems*, *weeded/ ploughed crop*, and *progressive bench terraces formed by vetiver stripes and trees*

[3] In 60 years population rose from 3.8 million in 1960 to 10.9 million people in 2017 (World Bank 2018).

[4] user's accuracy: probability that a sample unit of the same class belongs to the reference data.

[5] Producer's accuracy: probability with which a reference sample unit is correctly classified.

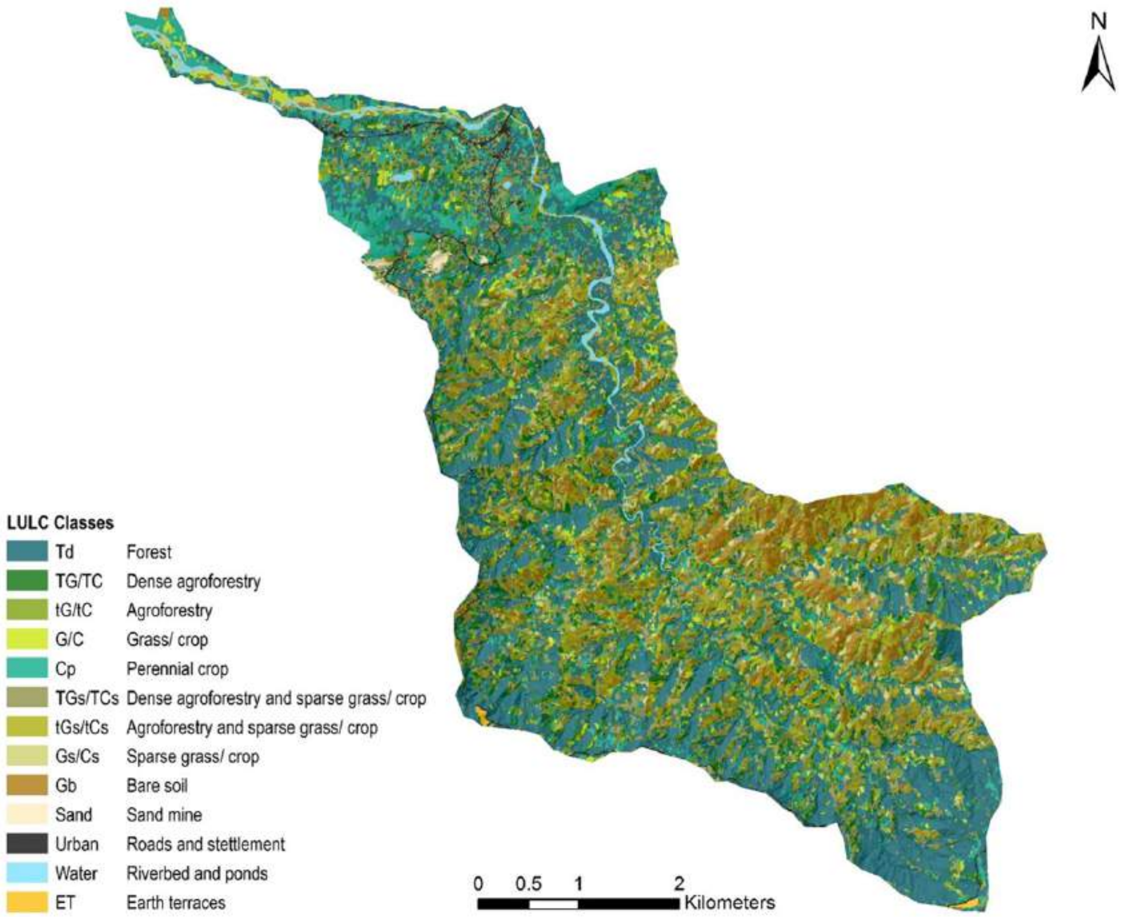

Figure 5.11: Land use and land cover map for the Cormier Watershed in Haiti resulting from the object-based image analysis

and producer's accuracy. The class agroforestry (tG/ tC) had both the lowest values for user's and producer's accuracy. The overall accuracy amounts to 0.68 and the Kappa coefficient to 0.63.

5.2.2 Discussion

In the literature, there are different evaluation schemes for the Kappa coefficient. According to Landis and Koch (1977), Kappa values above 0.8 represent high levels of agreement, the range between 0.6 and 0.8 represent moderate levels of agreement, and values below 0.4 represent weak agreement. For Ortiz et al. (1997), however, Kappa values of >0.2 are considered reasonable and values between 0.6 and 0.8 are even seen as very good. Hence, with a Kappa coefficient of 0.63, this LULC map can be considered of reasonable or even very good agreement. The following discusses the reasons for the resulted accuracy.

Satellite imagery: One crucial factor influencing the classification accuracy is the satellite imagery itself. As mentioned in Chapter 4.2.3.1, the purchased WorldView-2 image was distorted after the orthorectification process due to the extremely oblique off-nadir (27.5°) for the predominately mountainous study area. Moreover, the sunlight coming from the south throws shadows on the distorted

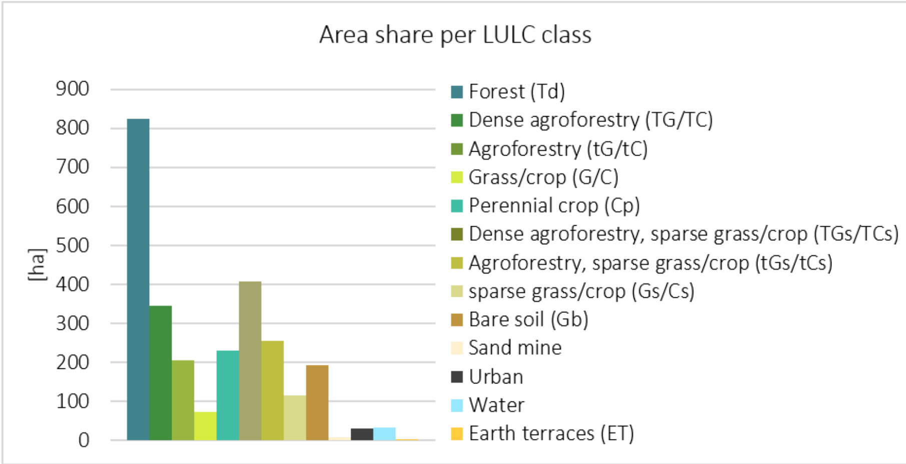

Figure 5.12: Area share per land use and land cover class for the Cormier watershed in Haiti

north-facing slopes (see Fig. 5.13). This affects the image segmentation as well as the land use classification. Therefore, in order to improve the accuracy, it is crucial that the imagery meets not only the research question's requirements (as mentioned in Chap. 4.2.1.1) but also the study area's context and particularities e.g. the topography and the slope aspect/ exposure.

Unclear boundaries between land use and land cover (natural starting point): Another important issue affecting the map's accuracy is the LULC in the study area. OBIA works better if the boundaries between the LULC classes are clear: many online tutorials for eCognition use examples of urban areas or agricultural land with rectangular or circular fields. In the present watershed in rural and mountainous Haiti, however, the natural interplay between LULC forms a mosaic-like structure, which often knows no clear boundaries between the land cover. These conditions complicate the entire classification process, from setting a suitable classification scheme to classification verifica-

Table 5.6: Land use land cover (LULC) error matrix showing the overall, producer's, and user's accuracies as well as the Kappa coefficient. All correct predictions are located in the diagonal of the table (highlighted in gray). The LULC classes are described in Tab. 4.3 and Fig. 5.11 (T.L.= manually classified thematic layers, includes the classes *water*, *urban*, *earth terraces* and *sand mine*)

		Reference data											
		Td	Cp	TGs/ TCs	tGs/ tCs	TG/ TC	tG/ tC	G/C	Gb	Gs/ Cs	T.L.	Total	User's Accuracy
Classification	**Td**	117	4	3	1	23	2	0	0	0	0	150	0.78
	Cp	10	26	0	0	3	1	1	0	0	0	41	0.63
	TGs/TCs	3	0	42	18	1	6	2	0	0	0	72	0.58
	tGs/tCs	0	0	2	33	0	0	0	2	10	0	47	0.70
	TG/TC	6	5	6	1	40	5	0	0	0	0	63	0.63
	tG/tC	1	2	2	1	11	17	3	0	1	0	38	0.45
	G/C	0	2	1	0	0	4	6	0	0	0	13	0.46
	Gb	0	0	0	5	0	0	0	26	0	0	31	0.84
	Gs/Cs	0	0	2	5	0	1	0	1	17	0	26	0.65
	T.L.	0	0	0	0	0	0	0	0	0	15	15	1.00
	Total	137	39	58	64	78	36	12	29	28	15	496	
	Producer's Accuracy	0.85	0.67	0.72	0.52	0.51	0.47	0.50	0.90	0.61	1.00		

Overall accuracy = 0.68, Kappa coefficient = 0.63

tion (see Huerlimann 2019). It is challenging to create a clearly differentiable classification scheme and to establish suitable criteria. However, the distinction also poses a problem for automatic and manual classification. It is difficult to select the right LULC class by estimating by eye how much of the image object is covered by tree canopy. Especially if there are many trees with a small canopy and / or the image is distorted and dark. As a result, categories that are well-delineated in theory are misclassified in practice.

Unclear image-object boundaries (segmentation): Unclear boundaries between land cover make the choice of the right segmentation scale harder. Too small scales result in segmenting each tree separately, and too large scale may join areas with different tree densities together in one image object. The classification accuracy could be improved with a better segmentation accuracy due to a less distorted satellite image. However, the accuracy of the segmentation was not further examined in this work. The testing and improving the segment geometries should be carried out in future analyses.

Hardly differentiable categories (classification): On the one hand, it is problematic that areas of different LULC categories have similar or identical digital values, e.g. bare soil, sparse grass/crop, dry riverbed and dirt roads all have similar spectral values. On the other hand, areas of the same category show a wide range of different values: e.g. the spectral values of grassland with one big mango tree (big canopy) is much higher than the one of grassland with small eucalyptus trees (small canopy). This might explain the low accuracy of the tG/tC class. With more spectral bands (hence, including yellow, red edge, coastal blue and near infrared 2), the differentiation might have been easier. The inclusion of object properties such as texture are common solutions in this regard and also used for this study. Since texture analysis in eCognition is very time consuming, this was done in ENVI and then imported in eCognition. However, the *feature space optimization* process in eCognition did not consider the texture images calculated in ENVI. Although very time consuming, further research need to consider the texture analysis function in eCognition.

Shadow and distortion (classification): As explained at the beginning of this section, the north-east facing slopes on the orthorectified WorldView-2 image are distorted and dark. For simplicity reasons, all image-objects first classified as shadow were attributed to the class Forest (Td) since the shadows were mostly caused by trees. This explains the high area share of *Td* in Figures 5.11 and 5.12. Looking back, one could have opted for dense agroforestry (TG/TC) or a mix between forest and dense agroforestry. This would have led to higher runoff values. For reasons of time and due to the scope of this master thesis, this was not changed retrospectively.

Training samples (classification): The quality of the classification depends decisively on the choice of training areas. On the one hand, these must be homogeneous and representative of the respective class, and on the other hand, must take account of the dispersion within the categories. Since the taining samples were selected manually, an attempt was made to meet these requirements as well as possible.

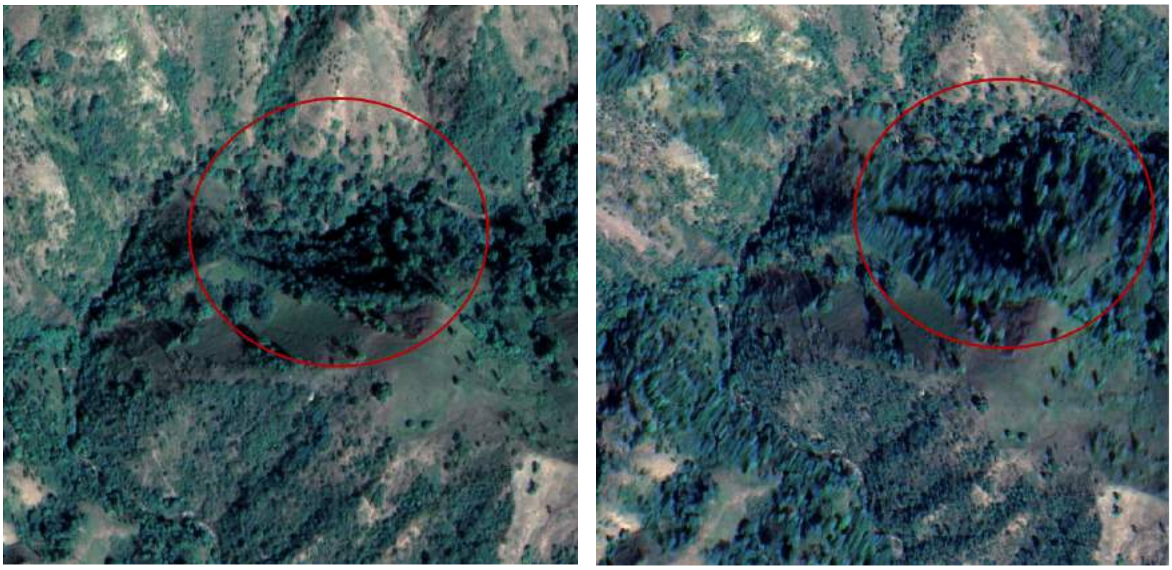

Figure 5.13: Distortion of the WorldView-2 image after the orthorectification process in ArcGIS. Left: original image; right: after orthorectification

Thus, the classification accuracy depends on various factors; the method for recording the reference data, their accuracy and the classification scheme have a significant influence on the analysis. Considering the quality of the satellite image, the users' experience with the software eCognition, the study areas complex land cover, and the Kappa coefficient of 0.63, this LULC map has a satisfying accuracy level for the further works step: the assessment of land use and land cover on potential runoff contribution.

5.3 Impact of land use and land cover on potential runoff contribution

In the following sections, the impact of LULC on the total watershed are presented. The first section will focus on the current LULC under different antecedent soil moisture conditions (AMC) (dry, average and wet). In the second section, the current LULC (average AMC) will be compared to scenarios with worsened and improved (once with vetiver terraces and another with agroforestry systems) LULC. All results in this chapter were calculated with the hydrologic soil groups (HSG) B and C (permeable to moderate permeable). The scenarios with HSG C and D (moderate permeable to almost impermeable) were only used for the discussion at the end of this chapter.

5.3.1 Impact of current land use and land cover on total watershed runoff

Figure 5.14 illustrates the current LULC situation: the LULC map on the left represents the LULC during/ at the end of the rainy season (same as in Fig. 5.11) and was therefore used for the calculations with average (II) and wet (III) antecedent soil moisture condition (AMC) (used for $LULC_{avrg}$ and $LULC_{wet}$); the one on the right side has been slightly adapted (see Chap. 4.2.4.1) and represents the LULC map at the end of the dry season (used for $LULC_{dry}$).

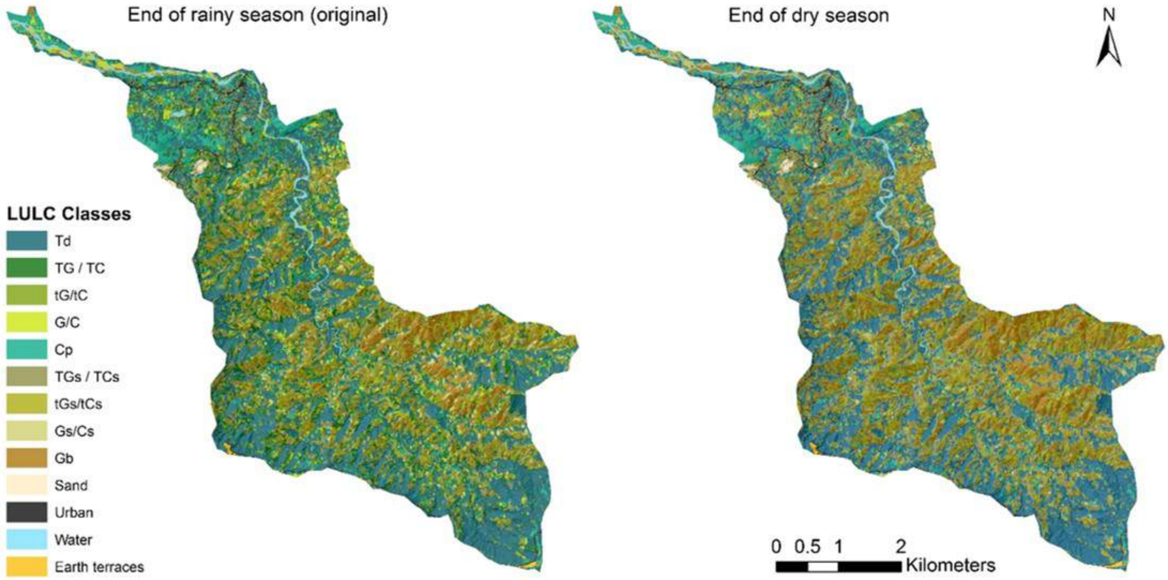

Figure 5.14: The current land use and land cover (LULC) for the Cormier watershed in Haiti. Left: original land use and land cover map resulting from object-based image analysis and representing the LULC during/ at the end of the rainy season (for $LULC_{avrg}$ & $LULC_{wet}$); right: the derived scenario for the end of the dry season (for $LULC_{dry}$)

Table 5.7: Potential Runoff for the current land use and land cover (LULC) in the Cormier Watershed in Haiti under dry ($LULC_{dry}$), average ($LULC_{avrg}$) and wet($LULC_{wet}$) antecedent soil moisture condition. The runoff is given in [mm] and in [%] of the total precipitation in the catchment by different scenarios of precipitation events (P8=8mm, P20=20mm, P70=70mm, P150=150mm, P300=300mm, P500=500mm)

	P8		P20		P70		P150		P300		P500	
	[mm]	*[%]*	[mm]	*[%]*	[mm]	*[%]*	[mm]	*[%]*	[mm]	*[%]*	[mm]	*[%]*
$LULC_{dry}$	0	*0*	0	*2*	17	*24*	70	*46*	197	*66*	384	*77*
$LULC_{avrg}$	0	*0*	0	*2*	16	*23*	68	*45*	195	*65*	381	*76*
$LULC_{wet}$	0	*2*	3	*15*	35	*50*	106	*70*	249	*83*	446	*89*

The total runoff for the current LULC under dry, average and wet AMC and under different precipitation scenarios is presented in Table 5.7. It is given in millimetres [mm] as well as in the percentage [%] of the rainfall that became runoff. The table shows that runoff increases with higher precipitation, though the relationship between runoff and precipitation is not linear: the more rainfall, the higher the percentage of runoff. $LULC_{avrg}$ and $LULC_{dry}$ have very similar runoff contributions. The poorer hydrologic condition (vegetation cover density) in $LULC_{dry}$ is compensated by the dryer AMC: poorer hydrologic condition generally results in more runoff, dryer soils, however, have a higher initial abstraction threshold. This means that, compared to wet soils, dry ones can absorb more precipitation before producing runoff. This also explains why $LULC_{wet}$ has by far the highest runoff contribution: the initial abstraction threshold is met fast. At an 8 mm rainfall, in all three scenarios ($LULC_{dry}$, $LULC_{avrg}$, and $LULC_{wet}$) hardly any precipitation is converted to runoff. At a 20 mm ($P20$) rainfall event, however, 15% of the precipitation runs off in $LULC_{wet}$ whereas in $LULC_{avrg}$ and $LULC_{dry}$ there is still almost no runoff. Moreover, at a 70 mm rainfall event ($P70$), $LULC_{avrg}$ and $LULC_{dry}$ only have half the runoff of $LULC_{wet}$. During very intense rainfall events (e.g. 500 mm, $P500$), the difference between the runoff amounts in $LULC_{wet}$, $LULC_{avrg}$ and $LULC_{dry}$ becomes smaller.

5.3.1.1 Hotspot areas for the current land use and land cover

In the following, hotspots of runoff contribution and land management are presented for the current LULC situation.

Hotspots with high runoff potential Figure 5.16 illustrates the areas where most rainfall is converted to runoff. The runoff is expressed as a percentage of the rainfall: the bluer, the less percent of the rainfall runs off, the redder, the more. Only the rainfall events $P20$, $P70$, $P150$ and $P300$ are shown because, at a rainfall of 8 mm, almost no HRU met the initial abstraction threshold. Thus, there was hardly any runoff. Conversely, at a rainfall of 500 mm, almost all rainfall runs off superficially. In $LULC_{avrge}$, the sparse vegetation on the south-facing side of the watershed (see Fig. 5.15) stands out with high percentage of runoff, especially at $P20$ and $P70$. The north-east-facing slopes, with more dense vegetation and, hence, less runoff can be identified easily (in blue for 70 mm and in yellow for 300 mm). For all rainfall events $\geq$ 20 mm the difference between $LULC_{dry}$ and $LULC_{wet}$ is rather pronounced. The riverbed, the ponds, the urban areas are the first spots to produce runoff during medium rainfall events of 20 to 70 mm in $LULC_{avrge}$. In $LULC_{wet}$ the areas with very sparse or no vegetation (Gb) produce a lot of runoff: at a 20 mm event, several hydrologic response units (HRU) converted more than 50% of rainfall in runoff and at a 70 mm rainfall event, only the HRUs classified as forest (Td) or dense agroforestry (TG/TC) had less than 50% of rainfall running off. In $LULC_{dry}$, only the HRUs classified as *Gb* (bare soil) and *Urban* converted more than 50% of rainfall into runoff (the class *water* does not exist in $LULC_{dry}$ due to the dried up riverbed and

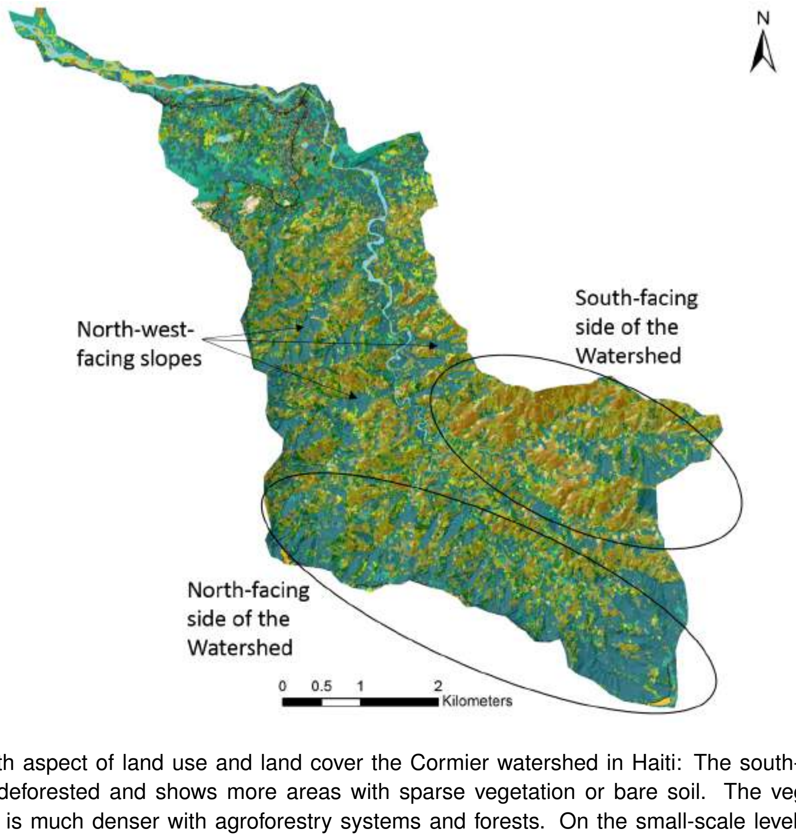

Figure 5.15: North-south aspect of land use and land cover the Cormier watershed in Haiti: The south-facing side of the watershed is more deforested and shows more areas with sparse vegetation or bare soil. The vegetation cover on the north-facing side is much denser with agroforestry systems and forests. On the small-scale level, it is rather a south-east/north-west aspect.

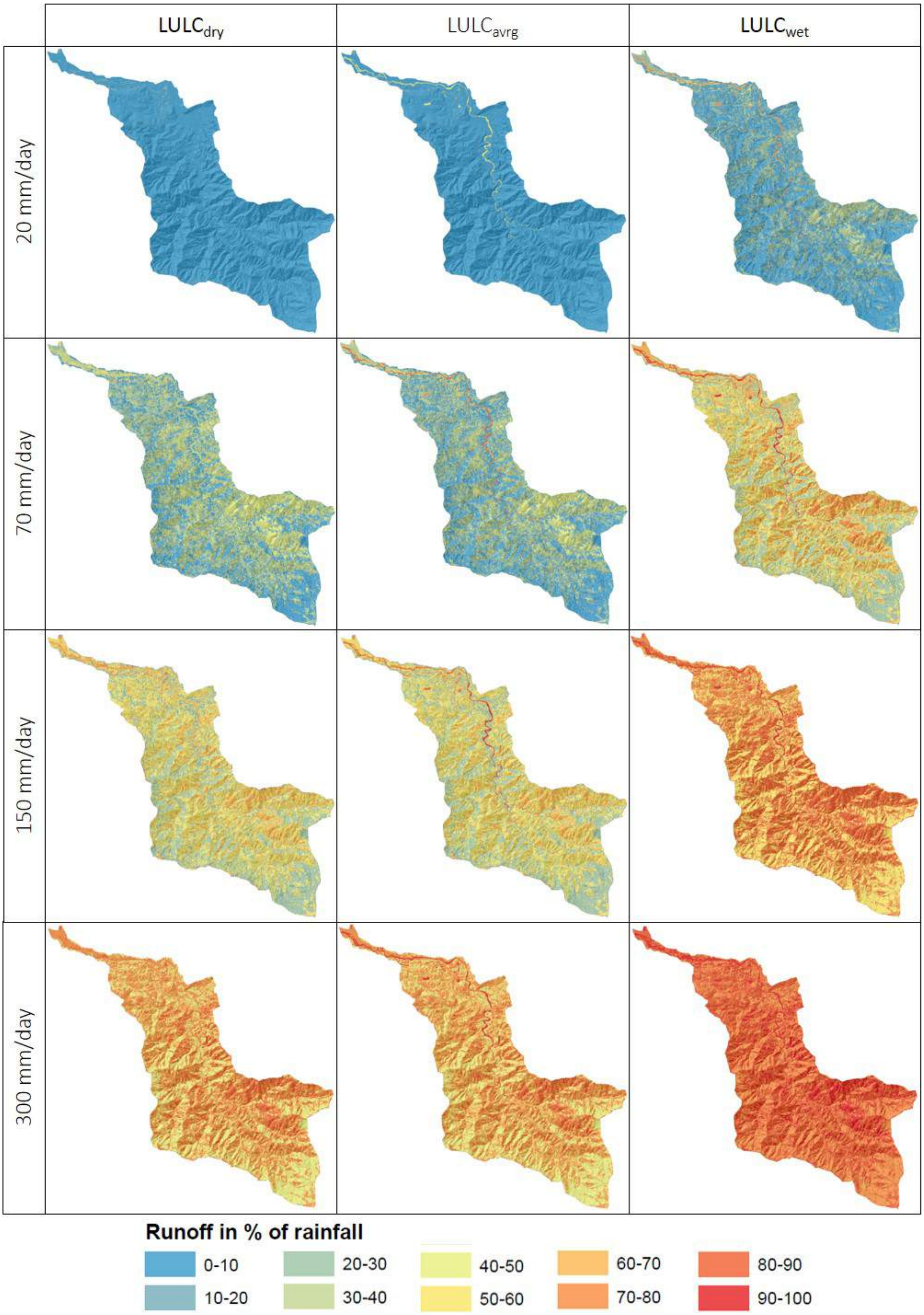

Figure 5.16: Potential runoff in percent of total rainfall for the current land use and land cover in the Cormier watershed in Haiti under dry ($LULC_{dry}$), average ($LULC_{avrg}$) and wet ($LULC_{wet}$) antecedent soil moisture condition and different precipitation scenarios

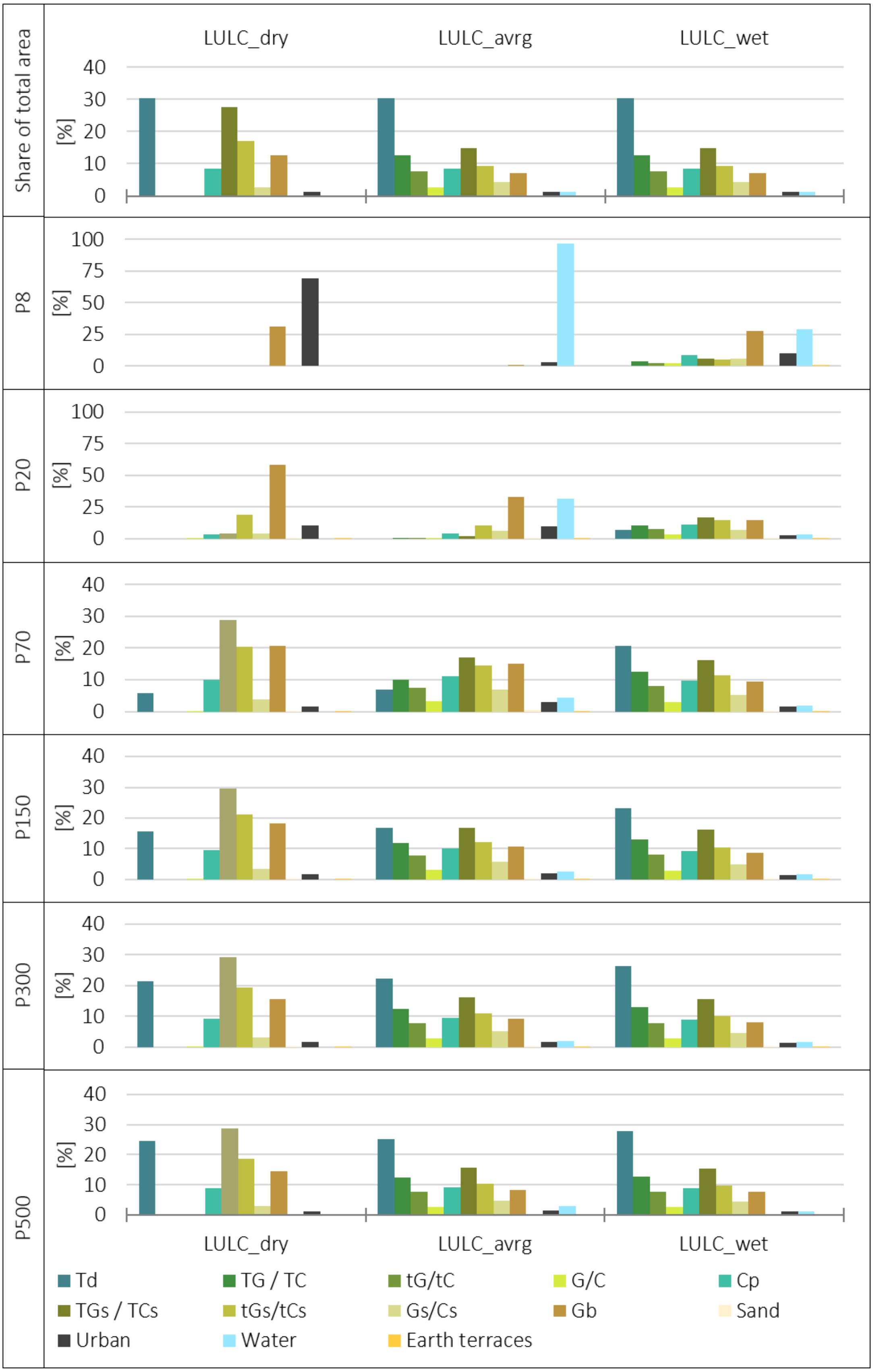

Figure 5.17: Potential runoff contribution of the current land use and land cover in percent to total runoff under dry ($LULC_{dry}$), average ($LULC_{avrg}$) and wet ($LULC_{wet}$) antecedent soil moisture condition and different precipitation scenarios

ponds). Although the runoff contribution increases with higher precipitation, a 150 mm rainfall event during wet season condition ($LULC_{wet}$) showed a higher percentage of rainfall converted to runoff than a 300 mm rainfall event during dry season condition ($LULC_{dry}$).

LULC classes with highest contribution to total watershed runoff Figure 5.17 gives an overview of the runoff contribution of the different LULC areas to the total watershed runoff. Regarding the current LULC with an average AMC ($LULC_{avrg}$), the runoff at an 8 mm rainfall ($P8$) was almost only produced in hydrologic response units (HRUs) classified as *Water*. Water has a very small initial abstraction threshold since the soil is already soaked. Therefore, its curve number is high. In Figure 5.17, one can observe that with smaller rainfall amount, areas with sparse vegetation cover contribute comparatively much to the total runoff. And although only 11% of the Cormier watershed in $LULC_{avrg}$ was classified as bare soil (Gb) or sparse grass/crop (Gs/Cs), together these two classes were responsible for 40% of the total runoff at a 20 mm rainfall event ($P20$). At 70 mm rainfall ($P70$), they still contributed to more than 20% of the total watershed runoff. However, the greater the rainfall, the more the runoff contribution of the different LULC categories reflects the percentage of the catchment area they cover as the different LULC areas show less and less difference in the infiltration capacities. Conversely to $LULC_{dry}$ and $LULC_{avrg}$, in $LULC_{wet}$ (at the end of the rainy season) the soils are all wet and therefore the initial abstraction is smaller for all LULC classes. Hence, difference in runoff contribution was more balanced. Nevertheless, water and bare soil (Gb) were the two classes most contributing to runoff during $P8$. Also here, Gb and Gs/Cs (together 11% of the area) contribute to almost 25% under 20 mm rainfall. Assuming that at the end of the dry season (Feb/Mar) i) vegetation cover becomes sparse and, hence, the hydrological condition worsens, and ii) the riverbed dries almost out and the ponds disappear, *Gb* and *Gs/Cs* also contribute a lot to the runoff in $LULC_{dry}$ compared to their share of the total watershed area (together 15% of the area): at a 20 mm rainfall event, two thirds (62%) of the total runoff occurs in these two LULC classes; at a 70 mm event they still contribute to almost 30% of the total runoff. However, the potential runoff in $LULC_{dry}$ is considerably smaller compared to the one in $LULC_{wet}$, especially for $P8$, $P20$ and $P70$ (see Tab. 5.7).

5.3.2 Scenarios with worsened and improved land use and land cover and their impacts on total watershed runoff

For the third research question, scenarios with different LULC were created based on the LULC map resulting from object-based image analysis in eCognition. The original and the derived LULC maps are shown in Figure 5.18. For details on how the three scenarios with worsened ($LULC_{poor}$) and improved ($LULC_{vetiver}$ with vetiver terraces and $LULC_{AF}$ with agroforestry systems) LULC were derived, see Chapter 4.2.5.

Table 5.8 shows the total runoff in millimetres [mm] and the percentage [%] of the rainfall that was converted to runoff for the current ($LULC_{avrg}$), worsened ($LULC_{poor}$) and improved ($LULC_{vetiver}$ & $LULC_{AF}$) LULC scenarios with average AMC and under the different precipitation scenarios. As in Table 5.7, the runoff increases with higher precipitation, though the relationship between

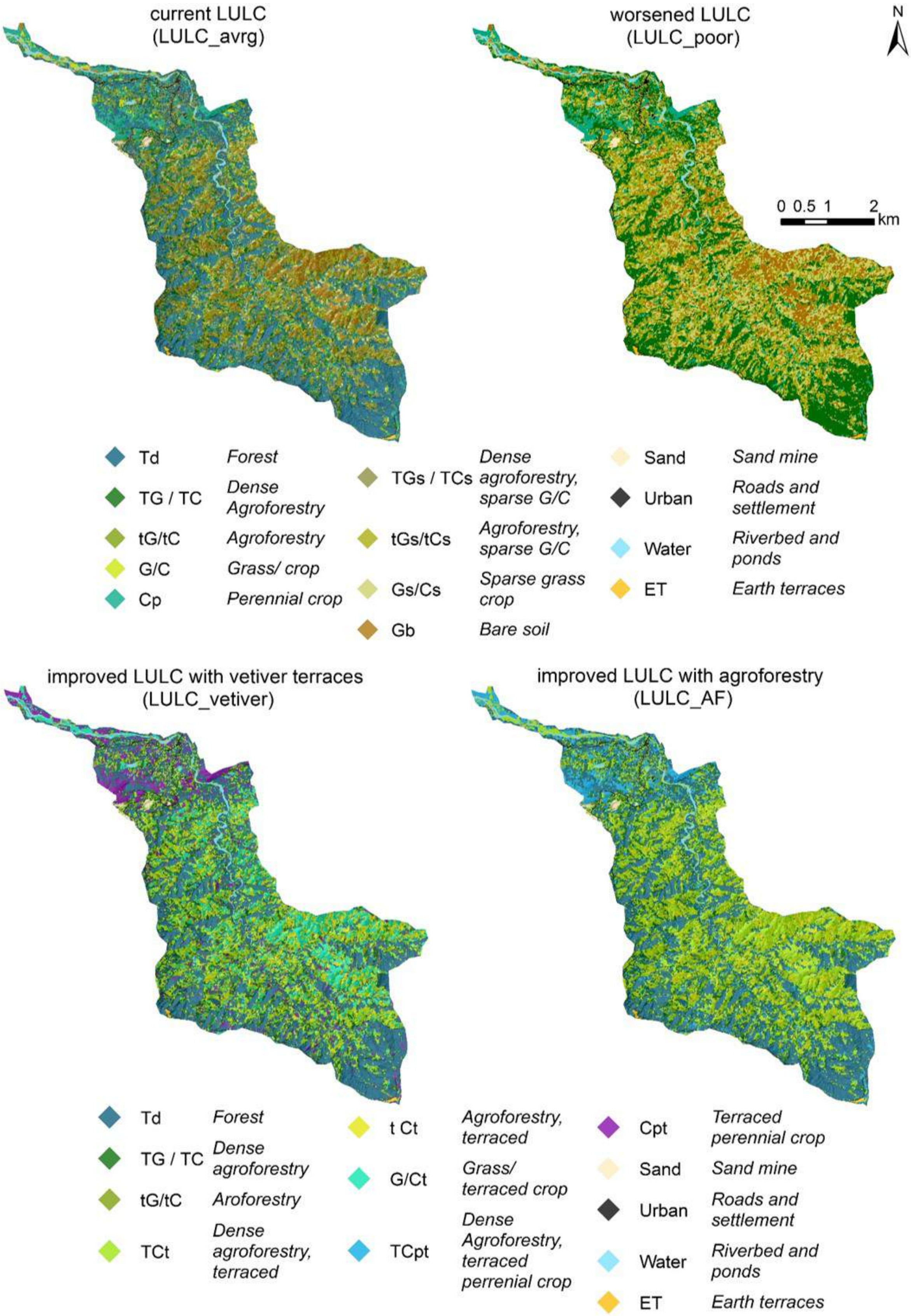

Figure 5.18: Land use and land cover (LULC) maps for the Cormier watershed in Haiti: the original LULC map resulting from object-based image analysis ($LULC_{avrg}$) and the three derived scenarios with worsened ($LULC_{poor}$) and improved ($LULC_{vetiver}$ with vetiver terraces and $LULC_{AF}$ with agroforestry systems) land management

runoff and precipitation is not linear. During all six rainfall events, $LULC_{poor}$ by far produces the most runoff, especially during moderate rainfall events with 20mm and 70mm: $LULC_{poor}$ produces 31% more runoff than $LULC_{avrg}$. Conversely, $LULC_{vetiver}$ and $LULC_{AF}$ only produce half as much (or even less) runoff as the current LULC $LULC_{avrg}$ during a 20mm event. At 70mm rainfall, $LULC_{vetiver}$ and $LULC_{AF}$ still produce 31% and 47% less runoff, respectively. With increasing rainfall amounts, the difference becomes less. Nevertheless, during 150mm (2yrs return period) and 300mm (10yrs return period) $LULC_{AF}$ still reduces the runoff amount about 19% and 9%, respectively, while $LULC_{poor}$ would increase runoff about the same percentage.

Table 5.8: Potential runoff for the current ($LULC_{avrg}$) land use land cover (LULC) as well as a worsened ($LULC_{poor}$), and two improved ($LULC_{vetiver}$ with vetiver terraces and $LULC_{AF}$ with agroforestry systems) LULC scenarios. They all represent an average antecedent soil moisture condition. The runoff is given in [mm] and in [%] of the total precipitation in the catchment by different scenarios of precipitation events (P8=8mm, P20=20mm, P70=70mm, P150=150mm, P300=300mm, P500=500mm)

	P8		P20		P70		P150		P300		P500	
	[mm]	*[%]*	[mm]	*[%]*	[mm]	*[%]*	[mm]	*[%]*	[mm]	*[%]*	[mm]	*[%]*
$LULC_{poor}$	0	*0*	1	*3*	22	*32*	84	*56*	220	*73*	413	*83*
$LULC_{now}$	0	*0*	0	*2*	16	*23*	68	*46*	195	*65*	381	*76*
$LULC_{vetiver}$	0	*0*	0	*1*	12	*17*	61	*40*	184	*61*	368	*74*
$LULC_{AF}$	0	*0*	0	*1*	11	*15*	57	*38*	179	*60*	362	*72*

5.3.2.1 Hotspot areas for the worsened and improved land use and land cover scenarios

In the following, hotspots of runoff contribution and of land management are presented for the current LULC ($LULC_{avrg}$) as well as for a worsened ($LULC_{poor}$), and two improved ($LULC_{vetiver}$ with vetiver terraces and $LULC_{AF}$ with agroforestry systems) LULC scenarios.

Like Figure 5.16, also Figure 5.19 illustrates the areas where most rainfall is converted to runoff, here, however, for the scenarios with worsened and improved LULC and the current LULC for comparison. The runoff is expressed as a percentage of the rainfall: the bluer, the less percent of the rainfall runs off, the redder, the more. Here, only the rainfall events $P70$, $P150$, $P300$ and $P500$ are shown because, at 8 mm and 20 mm rainfall events almost no HRU met the initial abstraction threshold. The differences between the current LULC ($LULC_{avrg}$) and the three scenarios with worsened ($LULC_{poor}$) and improved ($LULC_{vetiver}$ and $LULC_{poor}$) are clearly visible for the rainfall scenarios with $\geq$ 70. The riverbed, the ponds and the urban areas are the first spots to produce runoff during medium rainfall events of 70 mm. The sparse vegetation on the south-facing side of the watershed stands out with high percentage of runoff in $LULC_{poor}$ and $LULC_{avrge}$, especially at $P70$. In $LULC_{poor}$, a more homogenous runoff contribution can be observed due to the missing class *Td* (dense trees), especially at $P150$ and $P300$.

Figure 5.20 shows the average runoff potential for the current LULC ($LULC_{avrg}$) as well as the worsened ($LULC_{poor}$) and the two improved ($LULC_{vetiver}$ with vetiver terraces and $LULC_{AF}$ with agroforestry systems) LULC scenarios. They all represent an average antecedent soil moisture condition. The graph clearly shows that the potential runoff in the scenario with worsened LULC

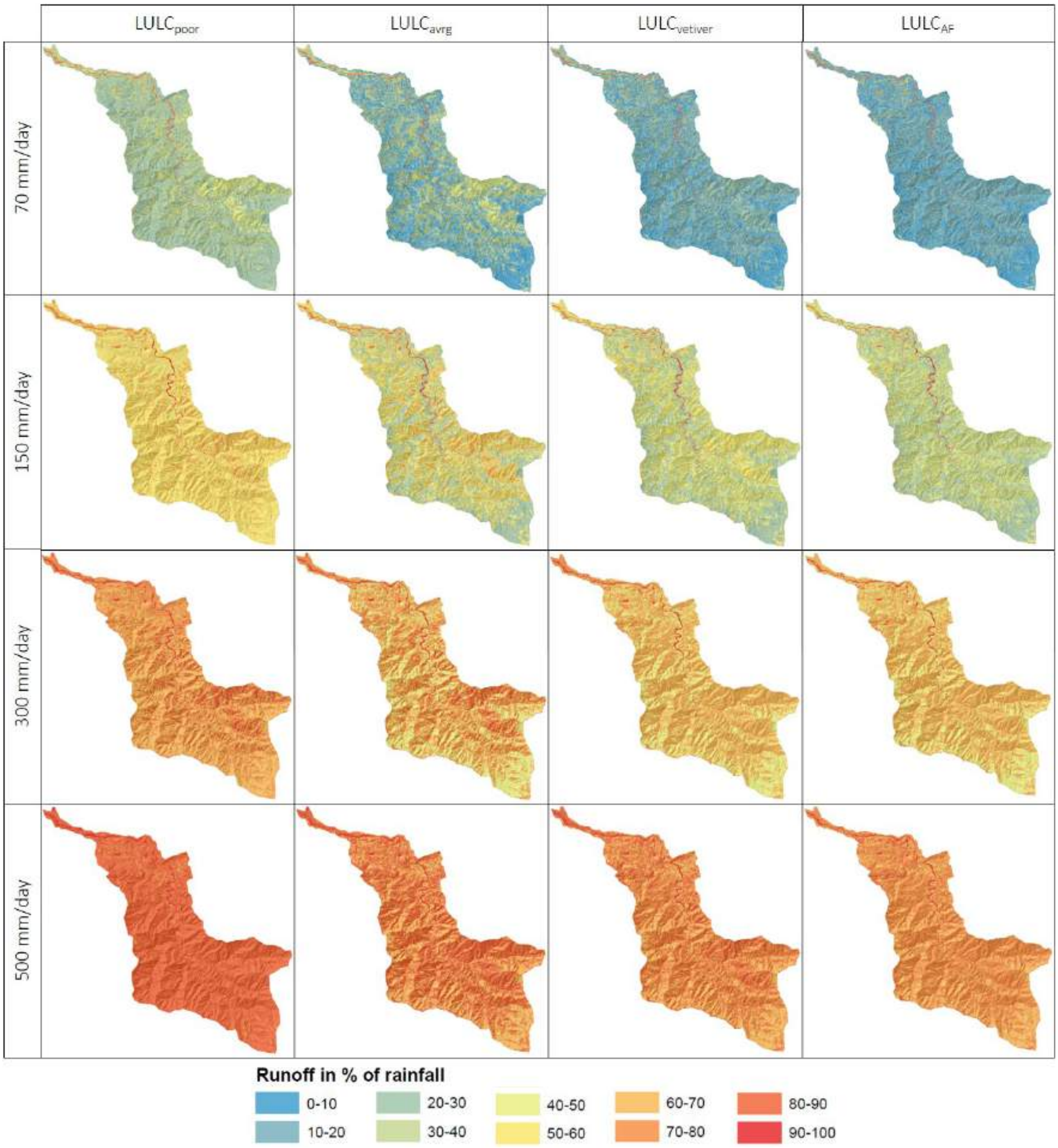

Figure 5.19: Potential runoff in percent of total rainfall for the current ($LULC_{avrg}$) land use land cover (LULC) as well as a worsened ($LULC_{poor}$), and two improved ($LULC_{vetiver}$ with vetiver terraces and $LULC_{AF}$ with agroforestry systems) LULC scenarios. They all represent an average antecedent soil moisture condition.

is higher than in the current LULC situation. Conversely, it shows the lower runoff potential of the two scenarios with improved LULC. During an 8mm rainfall event the four scenarios hardly differ. At a 20mm event, however, $LULC_{poor}$ already distinguishes itself from the other three. At a 70mm event, which represents the 95 percentile of the rainfall data analysed, the scenario improved with agroforestry systems shows the lowest runoff. During very intense rainfall events ($\geq$ 150mm) both improved scenarios distinguish themself from the current situation but the difference between both of them is small.

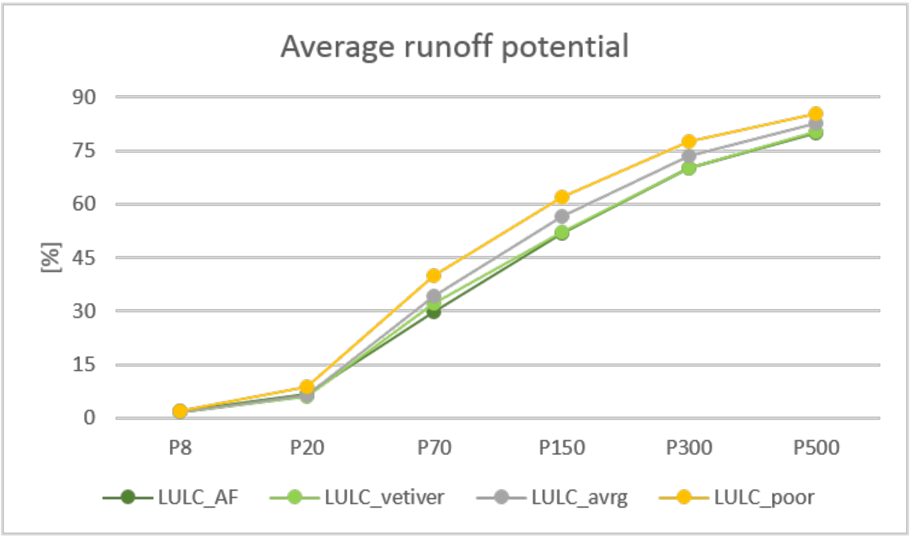

Figure 5.20: The average runoff potential for the current LULC ($LULC_{avrg}$) as well as the worsened ($LULC_{poor}$) and two improved ($LULC_{vetiver}$ with vetiver terraces and $LULC_{AF}$ with agroforestry systems) LULC scenarios. They all represent an average antecedent soil moisture condition. Precipitation scenarios: P8=8mm, P20=20mm, P70=70mm, P150=150mm, P300=300mm, P500=500mm

5.3.3 Discussion

The results presented in this chapter have to be understood as estimates based on models including the best of the understanding available concerning rainfall-runoff behaviour of watersheds with different LULC conditions, including basic soil types and slopes. Crucial parameters defining the runoff were estimated due to lack of data. Nevertheless, the results allow reflections on how the different hydrologic runoff units might respond to different amounts of precipitation. With such an analysis, the potential runoff could be assessed relative to land use. So far, there are no discharge data available for the Cormier river. Hence, the calculated potential runoff cannot be compared to empirical values. According to Frelat et al. (2012) and Gaucherel et al. (2017) about 45% of the amount of rainfall runs off and makes runoff water the main water cycle component in Haiti. The results in this thesis, however, show that this statements is not true for the Cormier watershed; even during rainfall events of 70 mm (represents the 95 percentile of the daily rainfall) the current LULC ($LULC_{avrg}$) had a potential runoff rate of less than 45%. Moreover, the potential runoff rate depends highly on the amount of rainfall during the certain event. In their studies, Frelat et al. (2012) and Gaucherel et al. (2017) do not specify how the got this percentage of runoff rate. It might be for a more degraded area with more precipitation.

According to Joss (2018), who was able to measure the runoff in his study area and compare it to the modelled results, the SCS-CN method tends to overestimate the potential runoff of rainfall events of more than 20 mm. He explains this with the fact that the SCS-CN method uses very basic parameters; the shape of the watershed and the sub-basins, the distance to the stream network, and the spatial distance of each HRU to the pour point are not considered. However, Joss (2018) assumes that the runoff curve number model works better for smaller watersheds, where spatial factors are negligible. Regarding the size of his study areas (9100km^2, 1406km^2 and 705km^2), the Cormier watershed is considered very small (30km^2). Therefore, the estimated potential runoff in the present thesis might be more accurate than in Joss' study. Nevertheless, some aspects need to be discussed in more detail.

Runoff after dry season: As expected, poor land use condition ($LULC_{poor}$) resulted in a higher runoff than improved land management with vetiver terraces ($LULC_{vetiver}$) and agroforestry systems ($LULC_{AF}$). However, regarding the results of Joss (2018), one might also have expected that the scenario of the end of the dry season would have resulted in a higher runoff than wet season condition due to the difference in vegetation cover (very sparse at the end of the dry season and abundant at the end of the wet season). However, the opposite resulted in the present thesis. The difference to Joss' results might be the antecedent soil moisture condition (AMC). It is assumed that Joss used AMC-II (average) for both dry and wet season scenarios. However, for the present thesis AMC-III (wet) was used for $LULC_{wet}$ and AMC-I (dry) for $LULC_{dry}$. Hence, although at the end of the rainy season, the vegetation is more abundant and the hydrologic condition is better, the soils are already heavily soaked and the initial abstraction threshold is quickly exceeded. At the end of the dry season, however, the soils are very dry and it takes a higher rainfall amounts to exceed the initial abstraction threshold. What the SCS-CN method seems to neglect concerning runoff in dry season conditions is the hydrophobicity (water repellency) of dry soils. This phenomenon has been observed in areas with eucalyptus forests after dry summers or droughts, for example, in Australia (Burch et al. 1989) and in Spain (Ferreira et al. 2000). Hydrophobicity is temporally variable, depends on soil moisture and has important implications for land use management and agriculture since it increases runoff and soil erosion (Doerr and Thomas 2000; Burch et al. 1989). In the Cormier watershed, NGOs have planted many eucalyptus trees in order to reforest the watershed and to stabilise slopes. Eucalyptus seemed a good option because even though people cut it for charcoal production, it regrows quickly. According to Jean Cars Dessin, the SCR SLM specialist in Léogâne, NGOs have stopped planting eucalyptus trees after recognising their environmental impacts (e.g. depletes the nutrients and moisture reserves of the soil). Nevertheless, during the field work in 2017, still many eucalyptus trees were observed at various sites. Considering this, the potential runoff in $LULC_{dry}$ might have been underestimated for the areas with a high proportion of eucalyptus trees.

Land use and land cover regarding disaster risk reduction and climate change adaptation According to Joss (2018), runoff depends highly on vegetation cover and "in extreme events, densely vegetated areas make the real difference in where more runoff is generated" (Joss 2018, p. i). For this thesis, Joss' statement cannot be confirmed. Joss's extreme event precipitation scenarios stop at 107 mm, whereas this thesis includes events with 150, 300 and 500 mm of daily rainfall. The findings presented above showed that the contribution of the LULC classes to the potential runoff depends strongly on the rainfall amount. The more intense the rainfall event is, the smaller the difference between the LULC classes becomes. This is illustrated in Figure 5.21 (for AMC-II). Joss' statement applies for the difference between bare soil (**Gb**) and dense trees (**Td**), which remained crucial even at $P300$ and $P500$. At 300 mm only about 50% of rainfall became runoff in HRU classified as *Td*, at 500 mm about 65%. This is also why the improved LULC scenario with agroforestry systems ($LULC_{AF}$) had a significantly smaller runoff for the total watershed. In HRUs with *Gb*, however, more than 80% of rainwater ran off at 300 mm and 90% at 500 mm. This coincides with results of Ogden et al. (2013). Ogden et al. compared hydrologic data of three catchments with contrasting LULC (forest, mosaic and pasture) and conclude that a 520 mm storm event did not overwhelm the ability of the forest catchment to store water. Their data also showed the crucial effect of LULC on peak runoff rates during events: The median peak runoff rates were larger in the mosaic[6] (1.4 times) and pasture catchments (1.7 times) than in the forest catchment. However, Joss' statement has to be relativised when it comes to Figure 5.21. The difference in converting rainfall to runoff between the LULC classes in-between (all vegetation classes except for bare soil (Gb) and forest (Td)) became very small with increasing rainfall (78%-84% for 300 mm and 86%-90% for 500 mm). Nevertheless, considering Ogden et al. (2013) findings that forest and mosaic catchments have lower peak runoff, it can be assumed that there must be a difference in peak runoff rate between these LULC classes although their runoff amount is approximately the same. The more obstacles such as trees, bushes, dense grass, vetiver terraces, wattle fences, etc. runoff has to pass, the slower it flows and the fewer damages are caused (see Durán Zuazo and Rodríguez Pleguezuelo 2008). Moreover, the slower the runoff flows, the longer the time the water has to infiltrate and the higher infiltration rated these LULC types have. Regarding these results, it can be concluded that by reforesting and increasing the bush, grass, crop and mulch cover of the whole watershed the disaster risk of floods and high peak runoff rates can be reduced drastically.

Regarding climate change adaptation, however, this might not be the best solution. As mentioned in Chapter 2.2.1, not only floods are expected to become more frequent, but also droughts; the single events and their amounts and intensities are expected to increase but the annual precipitation, as well as rainy days, are assumed to decrease, while the annual temperature is expected to rise.

[6] The *mosaic* catchment in Ogden et al. (2013) consisted of a dynamic mosaic of young forest of various ages, pasture, and subsistence agriculture.

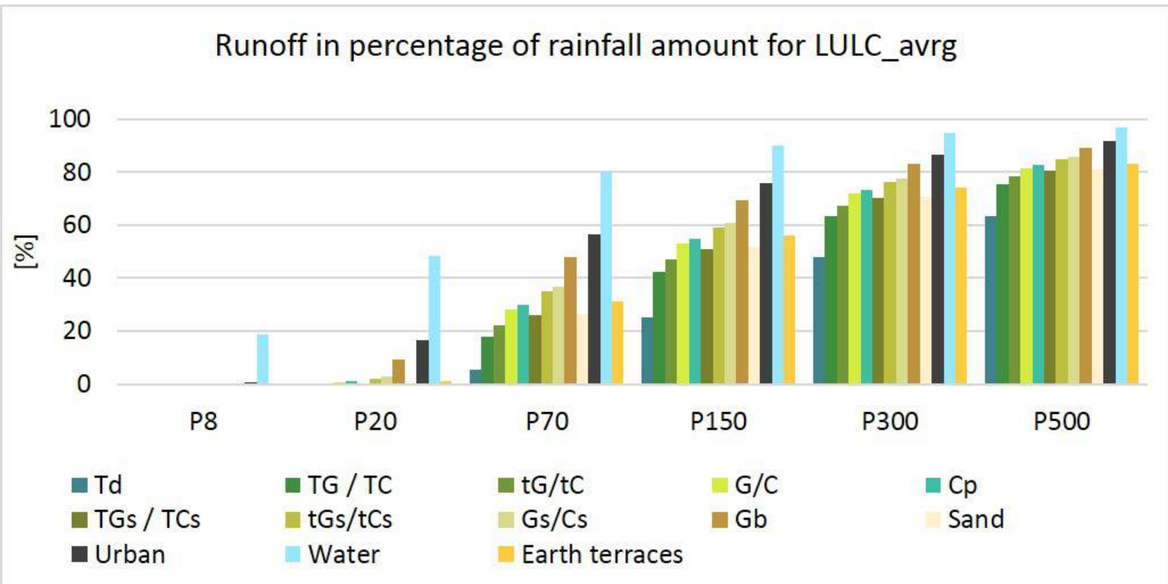

Figure 5.21: Potential runoff in percentage of rainfall amount for the current land use land cover scenario ($LULC_{avrg}$) for an extreme event (300mm). The more rainfall, the higher the percentage of the runoff compared to the rainfall amount and the smaller the difference between the LULC classes becomes. This was calculated for an average antecedent soil moisture condition)

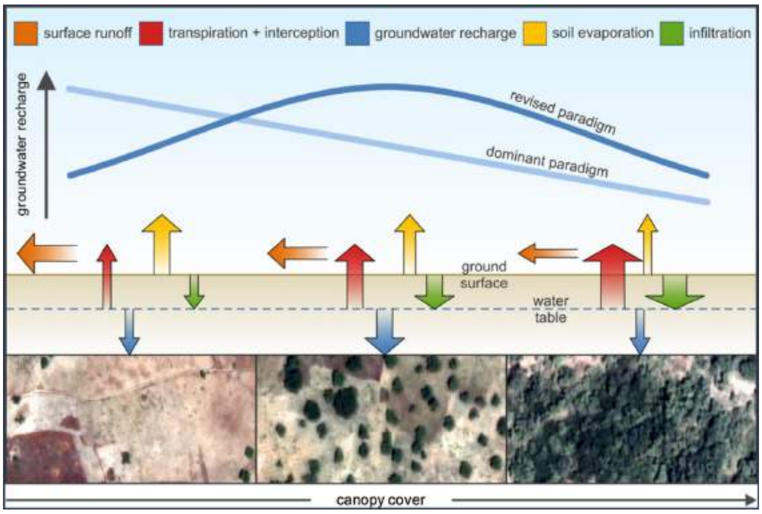

Figure 5.22: Conceptual water budget of the optimum tree cover theory. In seasonally dry tropical areas, the optimum ground water recharge occurs at intermediate tree cover. (Ellison et al. 2017, adapted from Ilstedt et al. (2016))

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Therefore, dry season base-flow, groundwater recharge and springs will become more and more important. A newer theory, the *optimum tree cover* theory (Ilstedt et al. 2016), suggests that although trees decrease water runoff and evaporation while improving water infiltration and ground water recharge, there seems to be an upper bound concerting tree cover density. According to Ilstedt et al. (2016), groundwater recharge reduces with high tree cover density when the hydrological gains from the infiltration are exceeded by losses due to transpiration and interception (see Fig. 5.3.3). However, this tree cover optimum depends, amongst other factors, on the tree size, age and species. Young trees and fast-growing species plantations have a relatively high water use compared to old-grown forests (Lal 1987; Ilstedt et al. 2016).

Hydrologic soil groups: The CN_2-value depends not only on the LULC but also on the hydrologic soil group (HSG) (see Tab. 4.6). The soil in the Cormier watershed is very clay-rich but shallow to moderately deep. For this thesis, they were classified as HSG B (ridges and slopes > 5%) and C (plains, valleys, and lower slopes 5%). In order to assess the influence of the hydrological soil groups on the results, the potential runoff for the current LULC under average AMC ($LULC_{avrg}$) was also calculated with less permeable, clay-rich soil groups where group B was converted to C and C to D soils (see Chap. 4.2.4.1 and Fig. 4.4). The results showed that especially the LULC classes with trees or good hydrologic condition differed a lot when changing the soil group (see Tab. 5.9). In the scenario with B and C soils dominating, good land cover has more potential to reduce runoff and therefore to reduce vulnerability towards torrential rains compared to a scenario with C and D soil groups dominating. However, this does not mean that when soils are very clayey and less permeable, land use and land cover do not matter. As discussed above, good vegetation cover as well as soil and water conservation technologies should be able to reduce the peak runoff rate. Moreover, tropical soils with finer texture require bioturbation and root penetration to guarantee the structure and porosity of the topsoil (Lal 1987). Good vegetation cover lead to healthy soils with stable structure to guarantee that macropores are sufficient and stable to drain prolonged and high rainfall events. Therefore, a forested area with HSG B/C, which is deforested and then suffers from land degradation, becomes bare soil with HSG C/D. This would mean a threefold increase in runoff at a rainfall with 2yrs return period (150 mm): 25% of runoff for forest (Td) with HSG B/C and 80% of runoff for bare soil (Gb) with HSG C/D (see Tab. 5.9). The other way round, if an area with bare soil is afforested, the soil becomes more permeable as well and the runoff would decrease by 55%.

The scenarios and their plausibility: $LULC_{dry}$ was derived from the original LULC map based on Google earth images. For the sake of simplicity, the hydrologic condition of all LULC classes was worsened. To improve on this scenario, one would need to have satellite imagery of February or March (end of the dry season) and generate a LULC map. For the scope of this thesis, whose purpose was to estimate the LULC potential in reducing runoff, the scenario seemed reasonable enough. When creating the improved scenarios $LULC_{vetiver}$ the curve number of *G/C* (grass/crop) was adjusted simulating (vetiver) terraces since the Swiss Red Cross is promoting this SLM technology in the area. At a later stage, also scenario with agroforestry was created ($LULC_{AF}$). Reforesting the watershed would not be realistic, agroforestry systems, however, are attractive for land users because it offers them production benefits. Nevertheless, the LULC class *Td* with a canopy cover of $\geq$ 50% was chosen, since during the field trip the agroforestry systems were observed to be rather densely vegetated. The LULC class *TG/TC* has a canopy cover of "only" 20-50%. As for $LULC_{dry}$, also for $LULC_{poor}$, the hydrologic condition of $LULC_{avrg}$ was worsened. Moreover, also deforestation was aggravated, representing a scenario where land degradation and desertification became more severe. Retrospectively, some changes could have been made regarding the HSGs. As mentioned before, the porosity of clay-rich tropical soils depends on the root penetration and bioturbation. Therefore, the scenario with poor land management ($LULC_{poor}$) should have been calculated with HSG C/D (less permeable) in order to be more realistic. This would have resulted in even more runoff of this scenario.

Table 5.9: Comparing the potential runoff of a 150 mm rainfall event for the current land use and land cover under average soil moisture condition: once with hydrologic soil groups C/D and once with B/C. Runoff is indicated as percentage of the 150 mm that run off superficially.

	Td	TG / TC	tG/tC	G/C	Cp	TGs / TCs	tGs/tCs	Gs/Cs	Gb
Runoff C/D	38	56	61	67	67	62	71	73	80
Runoff B/C	25	42	47	53	55	51	59	61	70
Difference [%]	-34	-24	-23	-21	-18	-18	-17	-16	-13

Chapter 6

Conclusion

Based on the results presented above, this chapter will answer the research questions, draw conclusions, critically examine certain aspects of the thesis, and take a look at possible follow-up research and projects.

6.1 Synthesis

During rain and hurricane seasons the Cormier river often floods. The main purpose of this master thesis is to assess the impact of the current and the potential of improved land management in the Cormier watershed to reduce vulnerability towards torrential rains as a natural hazard for disasters, including rainfall coming along with tropical storms and hurricanes. This was done by identifying and documenting different land use practices within the study area and then analysing the on-site impacts of those technologies on the human and natural environment (Q1), assessing the impact of the current land use and land cover (LULC) on runoff (Q2), and identifying the potential of improved land management practices to decrease runoff and the vulnerability towards torrential rains and tropical storms (Q3). The research questions can be answered as follows:

Q1 What on-site impacts (beneficial and disadvantageous) on human and natural environment do the sustainable land management (SLM) technologies have compared to the conventional land management (CLM) technologies?

This first research question intended to build up knowledge about the human-environment relationship of land management practices in the Cormier watershed. All five technologies assessed are applied under similar conditions (natural and human environment). Nevertheless, significant differences between the four SLM and the CLM technologies were found.

Important on-site benefits of the four assessed SLM technologies (vetiver terraces, agroforestry systems, Terra Preta raised gardenbeds and wattle fences for gully correction) are runoff reduction by providing obstacles and slowing down its velocity as well as by improving infiltration. Moreover, they reduce/ impede different types of land degradation, especially soil and water but also biodiversity degradation. They reduce soil loss as well as they accumulate soil and organic material coming from upstream, and therefore improve soil fertility, too. These SLM technologies also have a positive impact on crop production and increase food security. The CLM, however, performs poorly in almost all aspects assessed; it has a very negative impact in green water use efficiency, aggravates soil loss, causes and/or accelerates several types of soil, water and biodiversity degradation, downgrades crop production on the long term, thus, decreases food security. The only positive aspects are that in the short-term run it slightly improves farm income and that the know-how is readily available.

Regarding gradual climate change and climate-related extremes, all five technologies are facing some challenges. Nevertheless, SLM technologies appeared to be more resilient. Agroforestry, for instance, creates a favourable microclimate, which mitigates droughts impact. And although storms might strip the trees by blowing away the leaves and breaking the branches, agroforestry systems protect houses and plantations in it. Moreover, the trees usually recover quickly after just one rainy season. Vetiver terraces are very resistant to torrential rains, storms and to droughts, too. However, only the vetiver grass and terraces themselves; the technology cannot impede crop failure during severe storms and droughts. The same goes for wattle fences for gully corrections: once the fences are stable (when bamboo or moringa sticks have grown roots), they are very resilient to natural hazards but cannot impede crop failure. Terra Preta raised garden beds, who's main purpose it to increase food security, are often close to the house and can therefore be protected from droughts by irrigation and from storms by agroforestry systems which usually are found around houses as well.

The question arises as to why CLM is still widely used in the Cormier watershed event though SLM clearly has more advantages in terms of soil and water conservation, climate change adaptation and disaster risk reduction. The author of this thesis assumes that CLM is widely spread because, except for agroforestry, no other SLM technology has been applied in the area for long enough to be socially accepted and institutionalized. Vetiver terraces are a good alternative to CLM since both technologies can be used for planting similar crops. Major challenges for the social acceptance of vetiver terraces are that on the one hand there is no use for the vetiver grass except for mulching; neither human nor animals eat it. On the other hand, when establishing the terraces, the land users have to plant the vetiver in March/ April with the start of the first rainy season and are not allowed to cultivate the field for three months until the grass has deep enough roots. Since people in the Cormier watershed are considered relatively poor, and most of them are subsistence-oriented, they cannot afford to skip one rainy season. Although vetiver terraces are protective regarding soil stabilization and runoff reduction, they are not very productive for the land users.

Q2 How does current land use and land cover contribute to the total runoff from the watershed?

Land cover has a significant impact on the potential runoff contribution. Good hydrologic condition and high proportion of tree canopy covering the soil reduce the percentage of rainfall converting to runoff. For instance, in heavy rainfall events (with 150 mm rainfall) areas with dense agroforestry systems (TG/TC) have half the potential runoff of bare soil. However, the potential runoff depends on the volume of daily precipitation: the more it rains, the more runoff increases, and the smaller the difference between the LULC classes gets. Nevertheless, even in scenarios of very intense rainfall events (e.g. Hurricane Matthew with 500 mm), the difference of runoff contribution between areas with forests or dense agroforestry and bare soil was substantial with forests producing 32% and dense agroforestry 19% less runoff than bare soil. As for the hotspot areas, it is crucial to focus on areas with sparse vegetation cover and bare soil, as they represent 11% of the area of the watershed but contribute 40% of the total runoff during a 20 mm rainfall event (or 22% at a 70 mm event). These sparse vegetated areas with high runoff potential are mostly located on south-facing slopes, where CLM is dominant. Moreover, abundant vegetation increases the pores in the soil, thus improves the soil's permeability.

For this research question the runoff on current LULC was also analysed under wet and dry antecedent soil moisture conditions, hence, for the end of the dry ($LULC_{dry}$) and wet ($LULC_{wet}$) season, respectively. Due to the fact that at the end of the rainy season the soils are soaked, the initial abstraction was very small compared to the situation at the end of the dry season. This resulted in much more runoff: for instance, a rainfall event of 70 mm at the end of the wet season resulted in twice as much runoff than a 70 mm event at the end of the dry season. However, the potential runoff in $LULC_{dry}$ might have been underestimated due to the hydrophobicity of the soils caused by eucalyptus trees. Therefore, areas with high eucalyptus proportion need special attention for land management when focusing on reducing runoff.

Q3 How do the worsened and improved land management contribute to the total runoff from the watershed?

As expected, the worsened land management scenario resulted in more (e.g. 28% at 70 mm) and the improved scenarios in less runoff (-31% for vetiver terraces and -47% for agroforestry systems, both at 70 mm). During rainfall events of $\leq$ 70 mm (representing the 95-percentile of the daily rainfall data), $LULC_{AF}$ clearly performed best regarding runoff reduction. With increasing precipitation intensity, however, the difference in runoff potential between the two scenarios with improved LULC ($LULC_{AF}$ and $LULC_{vetiver}$) became smaller.

When comparing the runoff calculated with the hydrologic soil groups (HSG) B/C (more permeable) and the one with HSG C/D (less permeable), it was noted that especially for improved LULC classes the difference was essential: at a 300 mm rainfall event (10yrs return period), for instance, in the scenario with B/C 24% less rainfall was converted to runoff on areas with dense agroforestry systems. And since tropical soils, like ferralsols, with finer texture require bioturbation to maintain the structure and porosity of the topsoil, deforestation may decrease the permeability of the soil drastically.

What are the opportunities and potentials of improved land management practices to mitigate the impacts of climate change and to decrease vulnerability towards torrential rains and floods?

Regarding the main research question it can be concluded that agroforestry systems have a great potential in this environment. By reforesting the watershed and by increasing the bush, grass, crops and mulch cover, permeability of the soil could be improved and runoff reduced. Moreover, by slowing down the runoff speed and prolonging and spreading the runoff peak due to an increased travel time to reach the outlet of the watershed, devastating and destructive force of the runoff flow could be minimized.

6.2 Reflection

In particular, the classification process has to be scrutinized critically. The author assumes that with a better satellite image with a more vertical angle (off-nadir) and less shadows, the LULC classification could be substantially improved. Moreover, the object-based image analysis in eCognition offers a large room for manoeuvre. The user can choose between a variety of parameter settings, algorithms and features. This requires an intensive examination of the possibilities of the programme. Also, depending on the users' experience, the testing of the multiple combinations turns out to be very time-consuming. This and the fact that calculation processes may become complex, make it almost impossible to determine the best possible combination of parameter settings and process steps. For these reasons, this master thesis can only show one of many possible approaches to the classification and mapping of land use and land cover in the Cormier watershed. It cannot be ruled out that another approach will be faster or lead to better quality results.

Additionally, the data assessed with the WOCAT Questionnaires are mostly based on estimations. There are no empirical data of the study areas to verify the results. The same goes for the modelled potential runoff. Nevertheless, for data-scarce environments like this, this study helps to create knowledge where little data and measurements are available.

6.3 Outlook and recommendations

This master thesis assessed the opportunities and potentials of improved land management practices to mitigate the impacts of climate change and to decrease vulnerability towards torrential rains and floods. After the thesis, the author and the supervisor of this master thesis will have the chance to go back to Léogâne and discuss the results together with the Swiss Red Cross project staff and the land users.

For future research, the author recommends improving the data basis by encouraging NGOs and other organizations implementing projects to collaborate with the hydro-meteorological services and the land users of the country/ region/ watershed to install monitoring equipment in strategic sites in order to overcome the main challenge faced in this thesis: the data availability. Furthermore, applied research and studies including local and international students to assist in assessment, monitoring and scenario modelling would be really beneficial for further DRR implementations. Interesting follow-up studies would be the analysis of the impact of LULC on the runoff peak within the Cormier watershed as well as well as on soil erosion by water (for example, by adapting the methodological approach of the erosion risk map done for Switzerland by Gisler et al. (2011)). Together with the present thesis on potential runoff, these studies would further illustrate the opportunities of improved land management practices to increase resilience towards climate change and reduce vulnerability towards disasters triggered by natural hazards such as torrential rains and hurricanes. Moreover, in order to improve spreading SLM in the Cormier watershed, a qualitative study on the peoples motivation of choosing the unsustainable, conventional land use practice over the sustainable practices like vetiver terraces and agroforestry would be useful, too.

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Appendices

Appendix A - Legend of the geology map

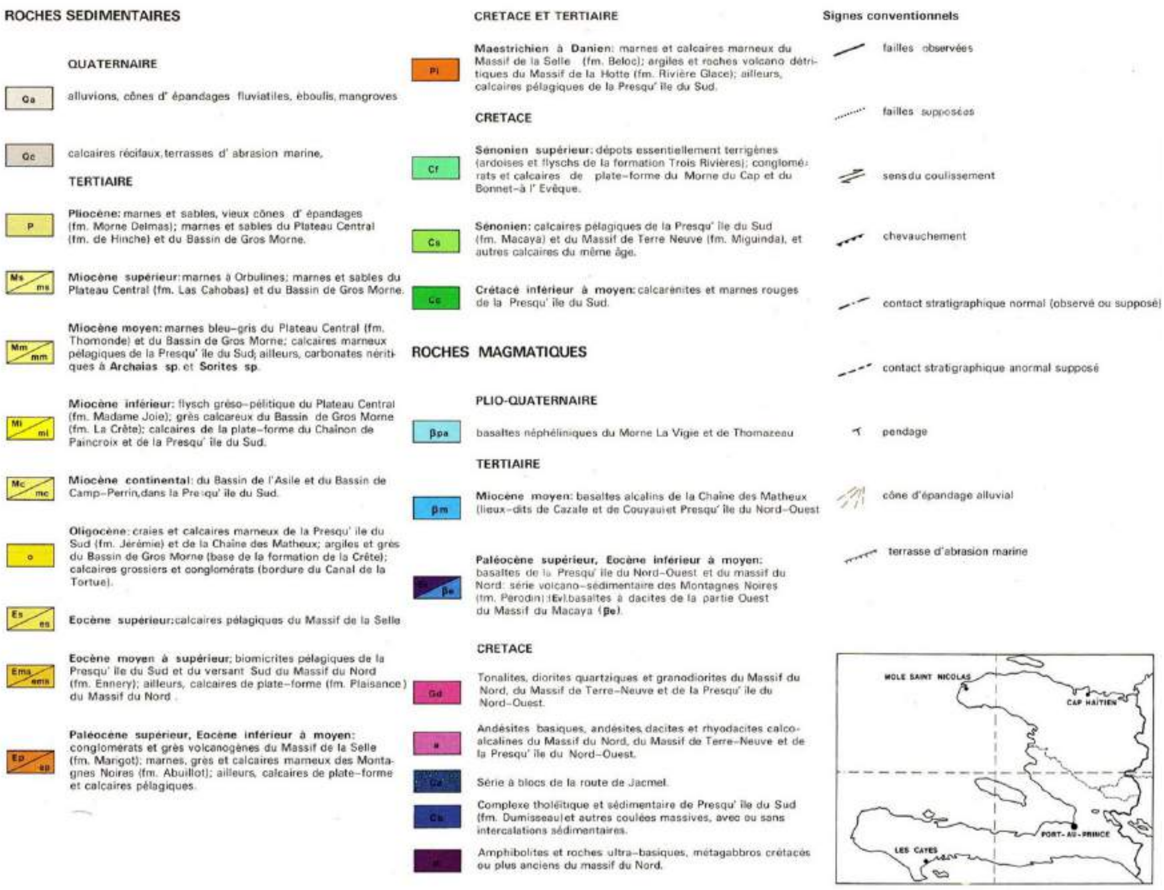

Figure A.1: Legend of the geology map (Fig. 2.4). Source: Lambert et al. (1987)

Appendix B - Feature space optimization (OBIA)

Layer values				Customized
Mean: • Brightness • NIR • Max. diff* • Pan* • Red • Green • Blue • Contrast • Dissimilarity • Entropy • Homogeneity • Ang. 2nd moment	Standard deviation: • NDVI • NIR • Pan* • Red • Green • Blue • Contrast • Dissimilarity • Entropy • Homogeneity • Ang. 2nd moment	Pixel-based: • Ratio - NIR* - Pan - Red* - Green* - Blue* - NDVI	To neighbours • Mean diff. to neighbour - NIR - Red • Mean diff. to darker neighbour - NIR - Red • Mean diff. to brighter neighbour - NIR* - Red*	• EVI* • MSAVI* • NDVI* • OSAVI* • SAVI*

Figure B.1: List of features for feature space optimization (eCognition identified the ones marked with an asterisk (*) as most suitable combination for separating the classes).

Appendix C - LULC classes and corresponding CN_2 values for each scenario

Table C.1: Land use and land cover classes and the corresponding CN_2 used for $LULC_{dry}$, $LULC_{wet}$, $LULC_{avrg}$ and $LULC_{poor}$

Land use land cover classes	Abb.	HSG				Specification; source
		C	D	C	D	
Urban	–	74	84	90	92	roads, houses; MacMillan: Urban
Water	–	95	95	95	95	waterbodies (riverbed and ponds); MacMillan: Water
Earth terraces	ET	55	71	79	84	big earth terraces for slope stabilisation, =(Ca(cont,terr,good)+Ge(fair))/2
Sand mine	Sand	68	80	87	91	sand mine; WOCAT: Ge(poor)
Bare soil	Gb	68	80	87	91	grassland, bare; WOCAT: Ge(poor)
Sparse grass/ crop	Gs&Cs	58	74	82	87	=(Gs+Cs)/2
Grass/ crop	G&C	51	68	78	84	=(G+C)/2
Perennial crop	Cp	55	69	78	83	perennial crop (contoured,good); WOCAT: Cp(cont,good)
Agroforestry with sparse grass/ crop	tGs&tCs	58	73	81	86	Agroforestry (<20% trees) with sparse grass or bare soil (Gb), =0.2*Td+0.8*Gb; MacMillan, adapted
Agroforestry with grass/ crop	tG&tC	44	64	74	80	Agroforestry (<20% trees) with good grass/crop (G&C), =0.2*Td+0.8*G&C; MacMillan, adapted
Dense agroforestry with sparse grass/ crop	TGs&TCs	48	67	75	81	Agroforestry (<50% trees) with sparse grass or bare soil (Gb), =0.4*Td+0.6*Gb; MacMillan, adapted
Dense agroforestry with grass/ crop	TG&TC	38	60	70	76	Agroforestry (<50% trees) with good grass/crop (G&C), =0.4*Td+0.6*G&C; MacMillan, adapted
Forest	Td	18	47	57	65	forest (dense trees); MacMillan: Td

Table C.2: Land use and land cover classes and the corresponding CN_2 used for $LULC_{vetiver}$ and $LULC_{AF}$

Land use land cover classes	**Abb.**	**HSG**				**Specification; source**
		A	**B**	**C**	**D**	
Urban	–	74	84	90	92	roads, houses; MacMillan: Urban
Water	–	95	95	95	95	waterbodies (riverbed and ponds); MacMillan: Water
Earth terraces	ET	55	71	79	84	big earth terraces for slope stabilisation, =(Ca(cont,terr,good)+Ge(fair))/2
Sand mine	Sand	68	80	87	91	sand mine; WOCAT: Ge(poor)
Agroforestry with grass/ crop	tG&tC	44	64	74	80	Agroforestry (<20% trees) with good grass/crop (G&C), =0.2*Td+0.8*G&C; MacMillan, adapted
Dense agroforestry with grass/ crop	TG&TC	38	60	70	76	Agroforestry (<50% trees) with good grass/crop (G&C), =0.4*Td+0.6*G&C; MacMillan, adapted
Terraced grass/ crop	G&Ct	50	67	76	82	=(G+Ct)/2
Terraced perennial crop	Cpt	51	67	76	80	perennial crop (contoured,terraced,good); WOCAT: Cp(cont,terr,good)
Agroforestry with terraced, perennial crop	tCpt	44	63	72	77	Agroforestry (<20% trees) with Cp and vetiver terraces, =0.2*Td+0.8*Ct MacMillan, adapted
Agroforestry with terraced crop	tCt	44	63	72	79	Agroforestry (<20% trees) with vetiver terraces, =0.2*Td+0.8*(0.5*Ct+0.5*G) MacMillan, adapted
Dense agroforestry with terraced crop	TCt	37	59	68	75	Agroforestry (<50% trees) with vetiver terraces, =0.4*Td+0.6*(0.5*Ct+0.5*G) MacMillan, adapted

E r k l ä r u n g

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