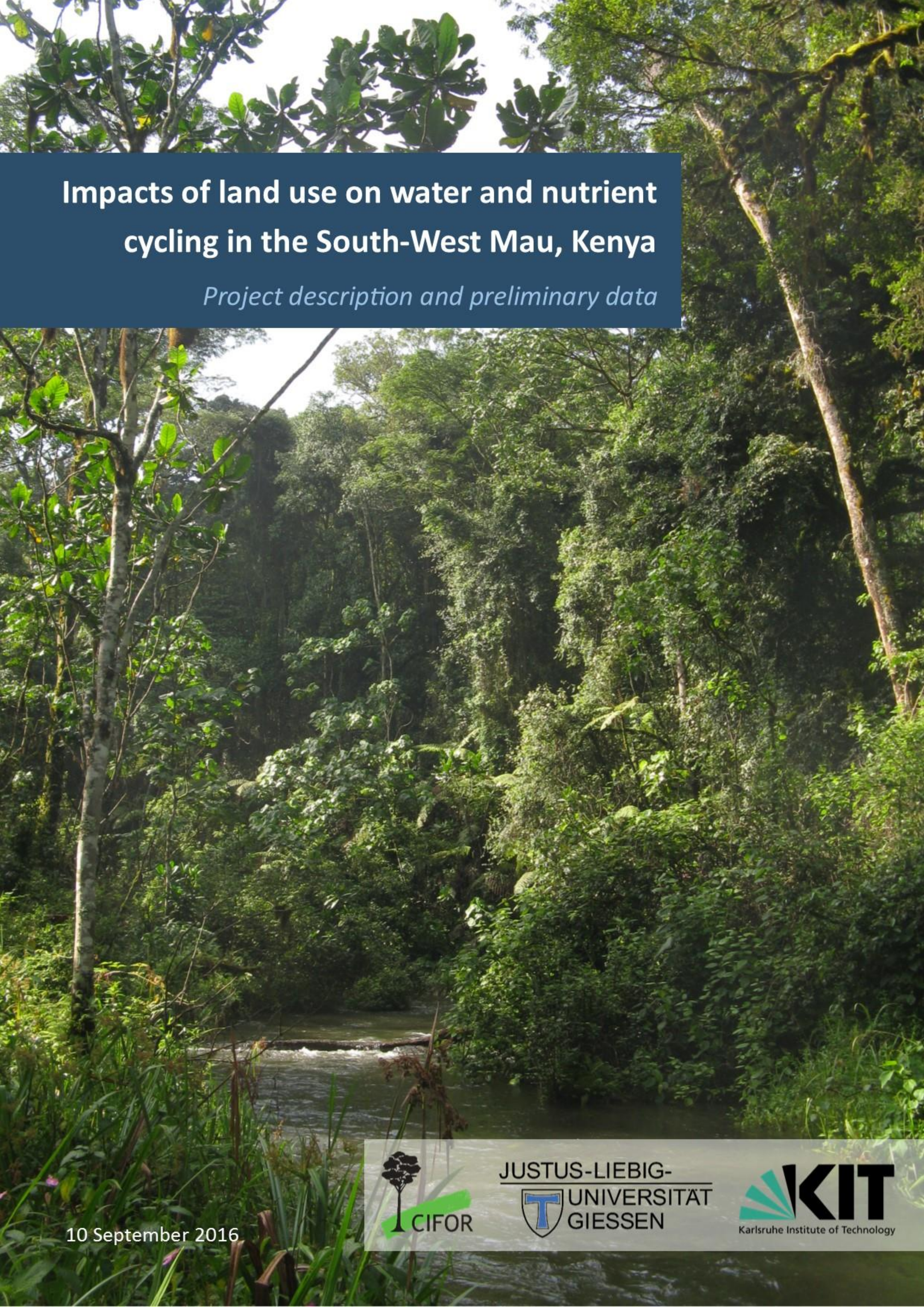
Impacts of land use on water and nutrient cycling in the South-West Mau, Kenya

Project description and preliminary data



10 September 2016

CIFOR

JUSTUS-LIEBIG-UNIVERSITÄT GIESSEN

KIT Karlsruhe Institute of Technology

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List of abbreviations

ADCP	Acoustic Doppler Current Profiler
ADV	Acoustic Doppler Velocimeter
C	Carbon
CIFOR	Centre for International Forestry Research
DOC	Dissolved organic carbon
EC	Electrical conductivity
ET	Evapotranspiration
ILR	Institute for Landscape Ecology and Resources Management
ILRI	International Livestock Research Institute
JLU	Justus-Liebig-Universität
KEFRI	Kenya Forest Research Institute
KIT	Karlsruhe Institute of Technology
LUC	Land use change
N	Nitrogen
NF	Natural forest
NO3-N	Nitrate
OUT	Main outlet
SHA	Smallholder agriculture
TDN	Total dissolved nitrogen
TOC	Total organic carbon
TTP	Tea/tree plantations
UV	Ultra-violet
WRMA	Water Resource Management Authority
ZEU	Centre for International Development and Environmental Research

Executive summary

With the current rise in interest and awareness of conserving forests as a source of clean water and other water-related ecosystem services, there is an increasing need to understand the effect of land use on water and nutrient cycling. While quite a number of such studies are available, the focus is often limited to the effect of land use on water yield, and less is known about the hydrological processes behind it and water quality. There is a lack of long-term field studies, especially in Africa. Furthermore, a fairly limited amount is known about tropical montane forests, an ecosystem providing many people with water, also in Kenya. This project aims to study the effect of land use on water and nutrient cycling in the South-West Mau, a region that has been affected significantly by land use change in the past decades. It is an important water source and the headwater area of the Sondu river.

The project uses a nested catchment approach, whereby three sub-catchments of 27 to 36 km² have been instrumented with automatic measurement equipment within a 1,023 km² catchment. The sub-catchments have a more or less homogeneous land use, either natural forest (NF), smallholder agriculture (SHA) or tea and tree plantations (TTP). The main catchment (OUT) has a mixture of the three land use types. The equipment measures water level, turbidity, total and dissolved organic carbon (TOC/DOC), nitrate (NO_3-N), electrical conductivity (EC) and stream temperature at 10-minute intervals. This data is complemented by rainfall data from nine stations distributed throughout the main catchment. Data collection in the sub-catchments started in October 2014. As the equipment only measures water level below the sensor, a relationship between water level and discharge (rating curve) has been developed specifically for each of the four measurement sites, by carrying out individual discharge measurements for a range of water levels to allow estimation of discharge.

Discharge patterns closely follow the precipitation pattern in all catchments. Lowest discharge is found in the smallholder area, which also receives the least rainfall. The year 2015 was marked by a long dry season and a wet short rainy season, which is also reflected in the discharge of all rivers.

Water quality parameters in the natural forest show a slightly different behaviour compared to those in the tea/tree plantations and the smallholder agriculture. Especially nitrate concentrations do not seem to be affected significantly by rainfall in the forest, except after the dry period of 2015, whereas nitrate concentrations generally increase in the two other catchments following the onset of the rains. Furthermore, a dilution effect shows for DOC in the tea catchment and, to a smaller extent, in the smallholder catchment at the peak of a rain event. Nitrate concentrations are generally lowest in the streams of the natural forest, followed by the smallholder agriculture and the tea/tree plantations. Nitrate concentrations at the outlet of the main catchment shows a pattern that reflects a combination of the concentrations and processes in the three sub-catchments.

Although the preliminary data presented here already shows a number of differences observed between the catchments, a long-term series complemented by further research is necessary to draw any conclusions regarding the effect of land use on water and nutrient cycling.

1 Introduction

1.1 Background

Forests worldwide are seen as important providers of water related ecosystem services, such as flood and soil erosion control, water supply and habitat function (Jasechko et al., 2013; Lele, 2009; Ojea et al., 2012; Spracklen et al., 2012). However, human-induced processes such as deforestation and land use change (LUC) can significantly affect the provisioning of these ecosystem services. The effect of LUC on hydrology has been studied for a number of decades. Several studies (e.g., Costa et al., 2003; Le Tellier et al., 2009; Legesse et al., 2003; Mungai et al., 2004) have investigated how discharge and water yield were affected by conversion of natural ecosystems to managed land uses, but there is a lack of studies focussing on the effect of LUC on stream water chemistry and hydrological processes, especially in regions like East Africa.

A large number of field and modelling studies (e.g., Germer et al., 2010; Giertz et al., 2005; Lana-Renault et al., 2011; Lin and Wei, 2008; Sullivan et al., 2004; Zimmermann et al., 2006) as well as some reviews (Bosch and Hewlett, 1982; Bruijnzeel, 2004, 1990; Sahin and Hall, 1996) draw the general conclusion that a reduction of forest cover leads to an increase in water yield. However, interpretation of these results should be done carefully: short-term measurements might not give reliable results, because it takes a long time before a new equilibrium is reached after permanent vegetation change (Brown et al., 2005). It is also widely recognized that deforestation affects the stream flow pattern, resulting in reduced stream flow during dry seasons and increased stream flow in wet seasons. This is attributed to reduced soil hydraulic conductivity and infiltration as well as a decrease in the capacity of surface soil to hold water because of a reduced litter layer and soil compaction (Costa et al., 2003), resulting in increased runoff during rainfall events (Duiker, 2011; Gol, 2009; Zimmermann et al., 2006). However, evidence to the contrary has been found as well. Important factors influencing the results are heterogeneity of the land use in a catchment (Bruijnzeel, 1990; Qian, 1983), proportion of area cleared of forest (Bosch and Hewlett, 1982; Sahin and Hall, 1996) and size of the studied catchment (D'Almeida et al., 2007; Wilk et al., 2001), but also geographical location and differing geological and climatic conditions (Ponette-González et al., 2014).

Stream water chemistry is a product of mixing of different water sources (Bustillo et al., 2011) and rainwater or snowmelt (Billett and Cresser, 1996; Caine and Thurman, 1990) as well as human activities that result in addition or removal of nutrients and other substances, modification of hydrological processes or LUC (Neill et al., 2006; Siwek et al., 2011). Forests are found to play an important role in maintaining water quality, such as lower levels of turbidity, nutrients, bacteria and metals compared to stream water coming from areas dominated by managed land use types (Knee and Encalada, 2014). There is evidence of increased nitrate loss (Williams et al., 1997), increased turbidity and solute load (Figueiredo et al., 2010) and increased suspended sediment and total nitrogen load (Hunter and Walton, 2008) as a consequence of deforestation and LUC. However, not all differences in stream water chemistry can be attributed to LUC, since physical characteristics such as soil depth (Lindell et al., 2010) and a combination of different factors, such as land cover, topography, geochemical reactivity, climate, inhabitation and area (Chuman et al., 2013; Reimann et al., 2009) also play a role.

Dissolved and particulate organic and inorganic carbon (C) and nitrogen (N) form part of stream water chemistry, but are also important links to primary production and carbon and nitrogen cycling in the ecosystem, since transport and exports are controlled by hydrology (Goller et al., 2006; Mitchell, 2001). There is also evidence that DOC concentrations are closely related to discharge (Hope et al. 1994, Raymond and Oh 2007), which suggests that potential changes in discharge patterns caused by deforestation could also result in changes in DOC export. Furthermore, rivers and streams are important carbon sources through outgassing, and sinks through burial of organic matter (Aufdenkampe et al., 2011; Cole et al., 2007; Mann et al., 2014). Therefore, any hydrological change caused by land use change is likely to result in an alteration of regional nutrient cycles, including changes in ecosystem C and N stocks or biosphere-atmosphere-hydrosphere exchange processes of C and N.

Although a large body of evidence shows the impacts of deforestation and LUC on water yield and seasonal flow patterns and to lesser extent on flow paths, stream water chemistry and nutrient cycling, the majority of research is focused on particular ecosystems in the temperate zone and the Neotropics. The variability in results of different studies does, however, suggest one cannot simply extrapolate results found in one area to another area. This implies that more detailed field research is necessary for lesser-studied ecosystems. One of such ecosystems is the tropical montane forest, known for its rich biodiversity (Burgess et al., 2007; Martínez et al., 2009) with a high degree of endemism (Gentry, 1992). These mountain ecosystems are also important for carbon storage (Spracklen and Righelato, 2014) and have been found to play an important role as regulator of the hydrological cycle at regional to subcontinental scales (Célleri and Feyen, 2009; Martínez et al., 2009). Although the latter fact is widely recognized, there is still a lack of understanding of hydrological processes, like the rainfall-runoff process and water storage within tropical montane forest ecosystems (Célleri and Feyen, 2009), especially in Africa and in relation to land use change (Bruijnzeel, 2001).

The Mau Forest in southwest Kenya is the country's largest closed canopy forest system as well as indigenous Afromontane forest, covering over 400,000 ha (Khamala, 2010). It is called one of Kenya's 'water towers', since it provides a large part of the Kenyan population with freshwater (Olang and Kundu, 2011). As a consequence of increased population pressure and political conflict, large parts of the Mau Forest have been degraded or transformed into other land use types, leading to a reduction of over 25% of forest cover (Government of Kenya, 2009). Much of the converted land has become susceptible to soil erosion and this supposedly resulted in a decrease in water quality in rivers and lakes downstream (Olang and Kundu, 2011). Moreover, deforestation has led to an increase of the seasonality of discharge, with rivers like the Mara running at very low levels during dry seasons thereby even affecting the unique Serengeti ecosystem due to decreased water access for wildlife (Milhahn, 2014). Although hydrological change in the Mau Forest and downstream areas is often attributed to land use change and the related loss of forest ecosystem services (e.g. Khamala 2010), very little reliable scientific evidence is available. The relevant research that has been carried out is often model based (e.g., Baker and Miller, 2013; Baldyga et al., 2004; Defersha and Melesse, 2012; Mango et al., 2011; Mati et al., 2008; Notter et al., 2007), lacking long-term measurements and thorough understanding of the rainfall-runoff process and water storage, which determine the flow regime in the area as well as downstream. These data and knowledge are essential for the assessment of the effect of land use on water related ecosystem services.

This project aims to understand the impact of land use on water and nutrient cycling in the South-West Mau. This part of the Mau Forest has undergone significant change, with 25% of the forest having been converted into tea/tree plantations and smallholder agriculture. The South-West Mau is also the headwater area of the Sondu river, which drains into Lake Victoria. Currently, there is much interest in taking measures to conserve and improve the state of the South-West Mau as well as the water quality and supply in the area. The data and knowledge generated in this project will be very useful to address such issues.

The project is run by the Centre for International Forestry Research (CIFOR) in Nairobi with the Institute for Landscape Ecology and Resources Management (ILR) of Justus Liebig University (JLU) Giessen and the Karlsruhe Institute of Technology (KIT) as project partners. On the ground, the project collaborates with the Water Resource Management Authority (WRMA) sub-regional office in Kericho, Kenya Forest Service (KFS), James Finlay (Kenya) Ltd. and Williamson Tea Kenya Ltd. Since March 2016, a second water monitoring project has started, jointly undertaken by WRMA, CIFOR, the German Corporation for International Cooperation (GIZ) and JLU Giessen. This project – also referred to as the citizen science project – aims to develop a low-cost monitoring strategy, using local communities around the rivers and the Water Resource Users Associations (WRUAs), to stimulate sustainable and high quality data collection on water levels in the Sondu basin. The project will later be expanded to also include water quality monitoring. The two projects are closely linked, since the high-resolution data from the automatic monitoring stations can be used to verify and optimize methods for low-cost data collection.

Currently there are three PhD students working on CIFOR’s water research: Suzanne Jacobs (CIFOR, JLU Giessen and KIT), Naomi Njue (CIFOR, JLU Giessen, University of Kabianga) and Björn Weeser (CIFOR, JLU Giessen, ZEU). Alongside this project, other research is being carried out by PhD students in the same area to look at carbon stocks and greenhouse gas emissions by Cristina Arias-Navarro (KIT, CIFOR) and Ibrahim Wanyama (CIFOR, International Livestock Research Institute ILRI), groundwater recharge in relation to land use by Steven Okoth (KIT, ILRI, South Eastern Kenya University) and forest degradation by Tom Bewernick (Wageningen University, CIFOR).

1.2 Objectives

The main aim of the project is to quantify the effect of land use on hydrological processes and biogeochemistry in an East African tropical montane forest based on long term field measurements. This can be sub-divided into the following objectives:

a. To quantify and compare **catchment hydrology** in catchments with natural forest, tea and tree plantations and smallholder agriculture and to understand the hydrological processes within these catchments.
b. To assess the effect of land use on **nutrient cycling**.

This report describes the set-up of the project and shows the preliminary results, collected between October 2014 and August 2016.

2 Project set-up

2.1 Study area

The selected study catchments lie within the eastern part of the Sondu-Miriu river basin (3,461 km²; Figure 1a). The elevation in the study area ranges between 1,700 and 2,700m and the geology is dominated by Tertiary lavas from early Miocene times (Edwards and Blackie, 1979; Figure 1b). The lower part of the study area is characterised by phonolites, but on higher elevations phonolitic nephelinites dominate (Binge, 1962; Woolley, 2001). The soils are stone free, heavily leached and uniform down to a depth of 6m (Edwards and Blackie, 1979); they are classified as mollic Andosols in the eastern part of the study area and humic Nitosols in the remaining majority of the area (Krhoda, 1988).

The area has a bi-modal rainfall pattern, with the 'long rains' falling between April and August and 'short rains' between October and December, while January and February are generally the driest months. Average annual precipitation in Kericho is 1,800 mm per year, but this value decreases with increasing elevation (Krhoda, 1988). The average temperature is 16°C at 2,000 m and does not vary much over the year (Edwards and Blackie, 1981; Krhoda, 1988). Average annual potential evapotranspiration (ET) is 1,570 mm per year, with decreasing ET with increasing elevation (Trabucco and Zomer, 2009).

The land use in the area is a mixture of commercial tea and tree plantations, natural forest and smallholder agriculture (Figure 1c). A belt of natural forest is found between 1,930 and 2,470 m elevation. Commercial and smallholder tea plantations are found below the natural forest, while higher elevations are dominated by smallholder or subsistence agriculture, where the main crops are maize, beans and potatoes. While the southwestern border of the natural forest of the South-West Mau is relatively stable since the establishment of the commercial tea farms, there is much encroachment and forest degradation through cattle grazing, collection of firewood, illegal logging and charcoal burning on the north-eastern side, where the forest borders the smallholder farms.

2.2 Site selection

A nested catchment approach was applied with three sub-catchments ranging from 27 km² to 36 km² within a catchment of 1,023 km². The selection criteria for the sub-catchments were:

- A more or less homogeneous land use: either natural forest (NF), smallholder agriculture (SHA), or tea and tree plantations (TTP);
- Accessibility by car, also during the rainy season; and
- Security of measurement equipment to be installed at the outlet of the catchment.

Identification of suitable study sites was carried out between May and July 2014 together with Alphonce Guzha (postdoctoral researcher at CIFOR at that time). We were supported with local knowledge by John Otuoma and David Langat from the Kenya Forest Research Institute (KEFRI) and Patrick Meya and Barnabas Kosgei of the sub-regional office of the Water Resource Management Authority (WRMA) in Kericho.

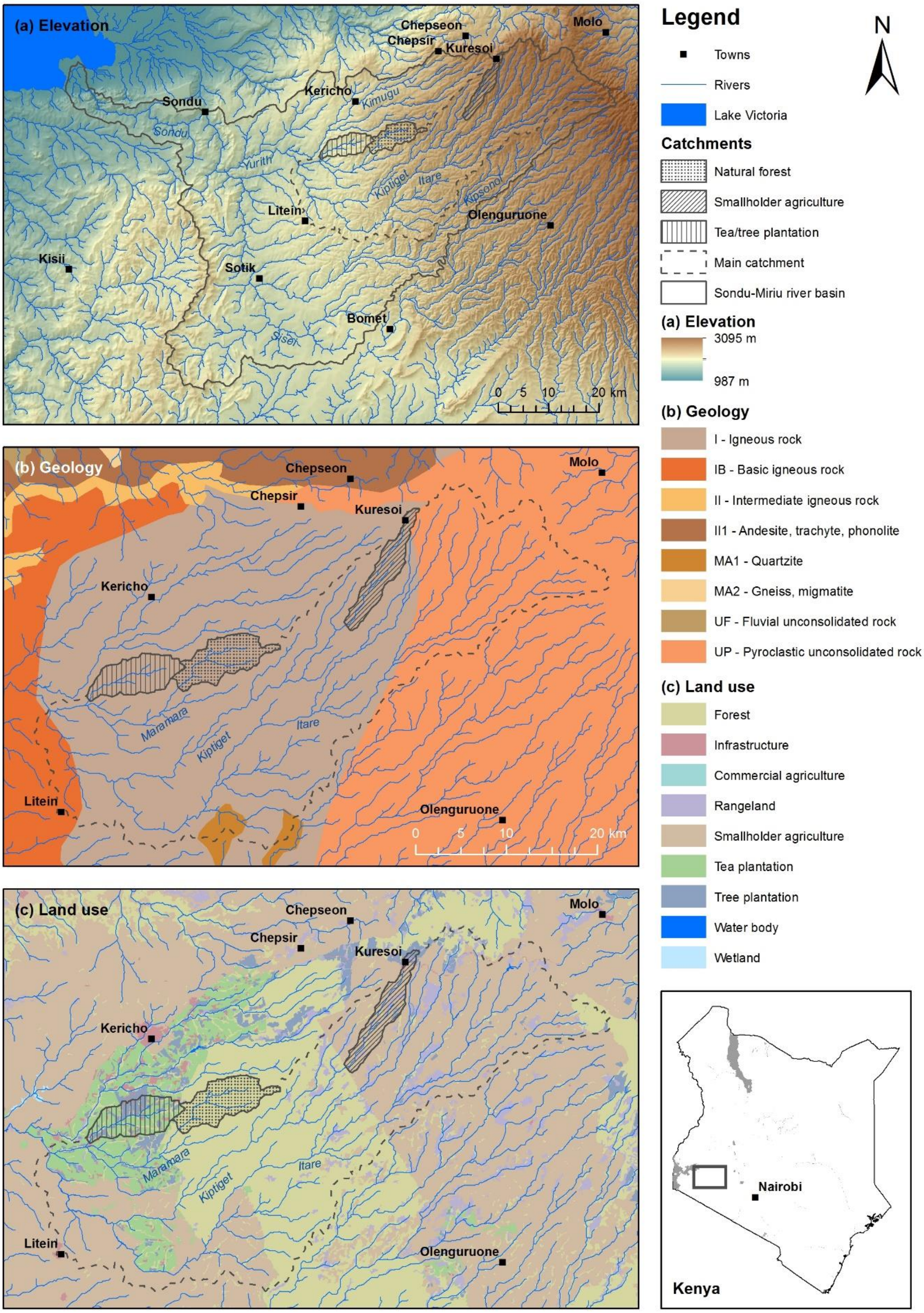

Figure 1 Maps of the study area: (a) elevation in the Sondu-Miriu river basin and surrounding area, (b) lithology in the main and sub-catchments, and (c) land use in the main and sub-catchments.

An additional site was selected downstream of all three sub-catchments (OUT, main catchment), where the effect of a mixture of land use types on water quality and quantity is measured. The data collected at this site will be used for modelling and upscaling of the data collected in the individual sub-catchments.

2.3 *Automatic measurement equipment*

The outlets of the four catchments are each instrumented with automatic measurement equipment (Figure 2a, b) that collects data on water level, stream water temperature, electrical conductivity (EC), total and dissolved organic carbon (TOC, DOC), nitrate (NO_3-N) and turbidity at 10 minute intervals. Each system consists of a water level sensor (VEGAPULS WL61, VEGA Grieshaber KG, Schiltach, Germany), EC probe (condu::lyser, s::can Messtechnik GmbH, Vienna, Austria) and spectrometer probe (UV-Vis spectrometry, 190 – 720 nm, resolution 2.5 nm) that measures the remaining water quality parameters (spectro::lyser, s::can Messtechnik GmbH, Vienna, Austria), connected to a datalogger (con::cube, s::can Messtechnik GmbH, Vienna, Austria). The systems run on solar power and have 24-hour security provided either by a company (at tea and forest site) or employed locals (at smallholder site and main outlet). The equipment at the forest and smallholder site started operating on the 11th and 12th of October 2014 respectively, while the installation in the tea plantation was finished on the 24th of October 1014.

The main outlet (of the 1,023 km² catchment) was instrumented six months later. Because the river at this point was wide and deep (during the rainy season), installation had to wait until the end of the dry season. The station started collecting data on the 20th of April 2015.

Figure 2 Instrumentation in the study catchments: (a) automatic measurement system for water quality and quantity, (b) water quality sensors with spectrometer (left) and electrical conductivity probe (right), (c) throughfall tipping bucket, (d) tipping bucket and (e) weather station.

2.4 *Weather data*

To complement the river data, a number of weather and rainfall stations were set up in the area in October and November 2014 (Figure 3). One weather station (Figure 2e), collecting data on rainfall, temperature, relative humidity, wind speed and direction, solar irradiance and soil moisture, was installed at the outlet of the smallholder catchment and one just outside the tea/tree plantation catchment at a secondary school within Finlays tea estate. However, the latter was relocated to the Marinyn Airstrip in Finlays tea estate, 2 km southeast of the original location, just inside the tea/tree plantation catchment on the 16th of September 2015. A third weather station is located at Kericho Forest Station, approx. 6 km outside the main catchment.

To capture the variability in rainfall throughout the area, six additional tipping buckets that automatically collect data on rainfall totals and intensity (Figure 2d) were installed: two in the smallholder catchment, one at the outlet of the forest catchment, two in the tea catchment and one at the outlet of the main catchment (Figure 3). Furthermore, two throughfall tipping buckets (Figure 2c) were installed in the natural forest to get an idea of rainfall interception by the forest canopy. These are, however, located quite close to each other and to the outlet of the catchment due to security and accessibility issues and will not be able capture the variability in rainfall and throughfall in the whole forest catchment.

Rainfall for each of the catchments is calculated using a weighted average of the stations within or close to the respective catchment. The weights for a station are calculated using Thiessen polygons that represent the area a station covers within the catchment. Whenever a station is not working, new weights are calculated to cover for the data gap.

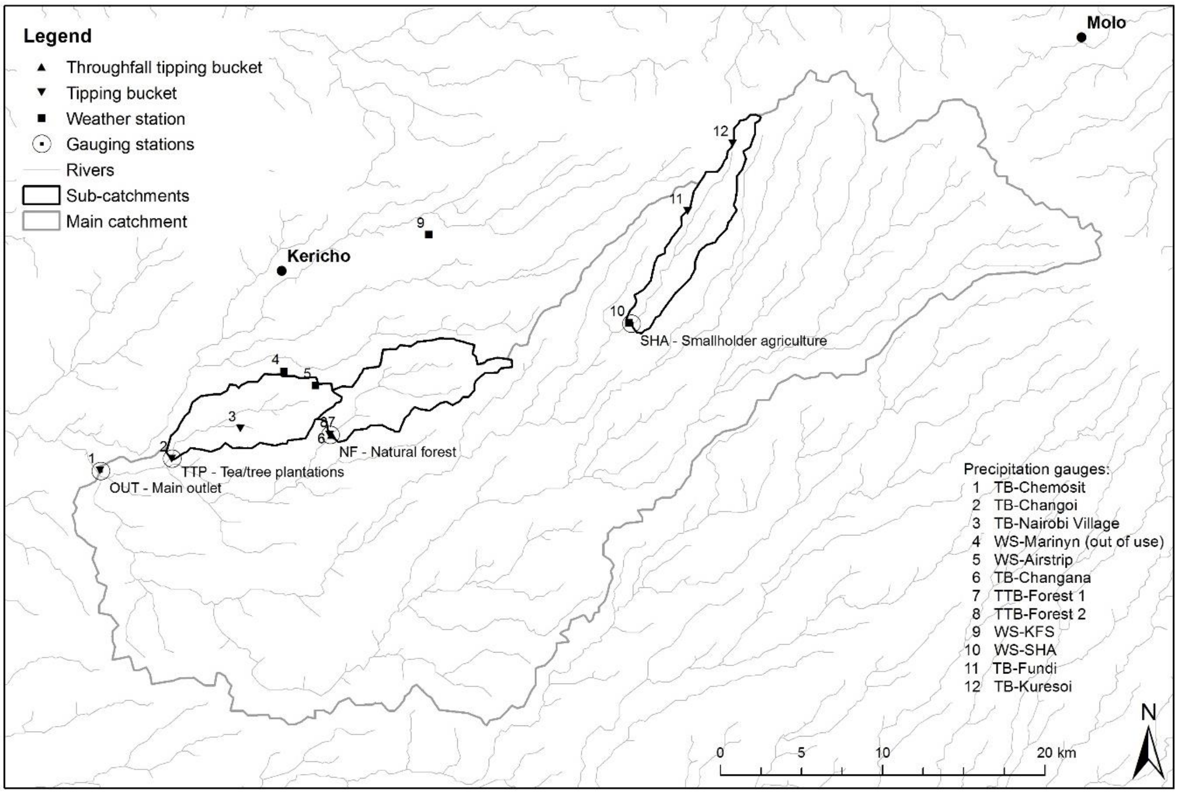

Figure 3 Location of the instruments in the study area.

3 Preliminary results

This chapter shows the preliminary data collected by the automatic systems between the 12th of October 2014 and the 31st of August 2016. It has to be noted that the data presented in this report is raw data. Currently, only values collected during instrument malfunction are removed from the dataset. However, for some parameters further data processing is necessary. This mainly applies for the data on TOC/DOC concentrations. These parameters are affected by biofilm development on the sensor, which has to be removed manually every week. Although long-term trends observed in the unprocessed data – especially at the natural forest site – are therefore not reliable, responses of the parameters to, for example, rainfall events are not affected by the issue.

3.1 Catchment hydrology

The water level data obtained by the water level sensor is used to estimate discharge, using a stage-discharge relationship or rating curve developed specifically for each station (Appendix 1). The discharge patterns shown in Figure 4 closely follow the precipitation (rainfall) patterns, with a slight delay in response in all catchments. Actual discharge from the smallholder catchment is lower than that of the two other sub-catchments. Calculation of specific discharge or runoff (actual discharge divided by catchment area) allows for comparison of discharge data between catchments with different sizes. In this case, specific discharge also shows a lower value for the smallholder catchment. This contradicts the general idea that streamflow in non-forested catchments is higher during the wet season than in forested catchments, but is most likely explained by a lower total rainfall amount in the smallholder catchment (Table 1). The ratio of runoff versus rainfall in 2015 is similar in the three catchments, ranging from 0.35 in the forest and smallholder catchment to 0.37 in the tea catchment.

Table 1 Total rainfall and runoff in the three sub-catchments in 2015.

Catchment	**Rainfall** mm/yr	**Runoff** mm/yr	**Runoff/rainfall ratio**
Natural forest	2,045	718	0.35
Smallholder agriculture	1,627	574	0.35
Tea/tree plantations	1,980	735	0.37

Looking in more detail at the rainfall and specific discharge data, there are a number of interesting observations. First of all, monthly rainfall data (Figure 5) shows less rainfall during the dry season of 2015 (January to March) compared to 2016, especially in the smallholder catchment. Furthermore, the rainfall during the short rains of November and December 2015 was higher than in the previous year. This is reflected in higher specific discharge in the corresponding months. Interestingly, specific discharge in April and May 2016 is higher – except in the natural forest – while the rainfall is similar or lower than in 2015. This suggests there is a considerable lag in the response of discharge to rainfall and part of the specific discharge of the river originates from the precipitation fallen in earlier months.

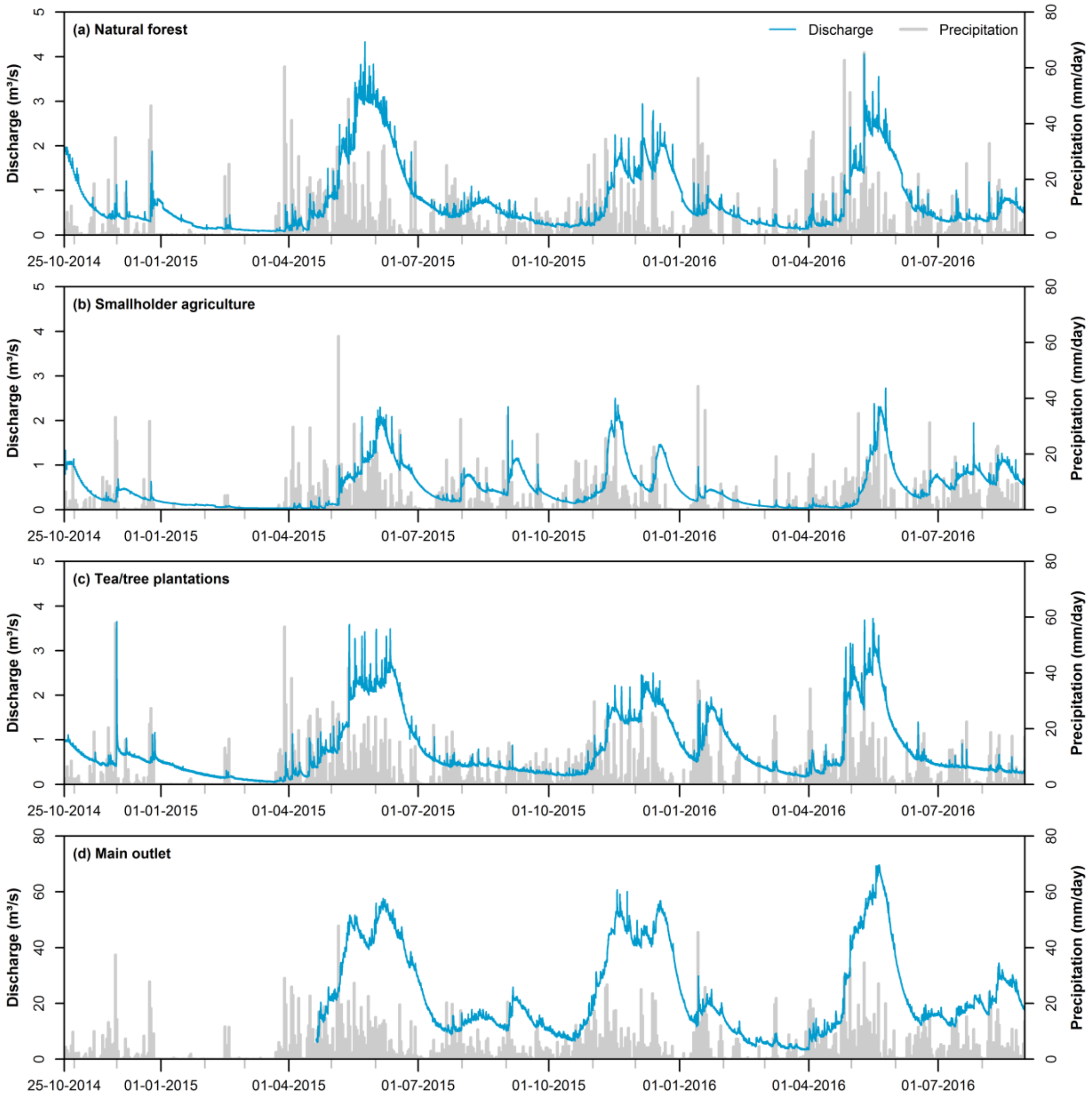

Figure 4 Discharge and daily precipitation over the study period for the (a) natural forest, (b) smallholder agriculture, (c) tea/tree plantations and (d) main outlet. Note the different scale in (d) for the discharge data (y-axis).

3.2 Nutrient cycling

3.2.1 Temporal patterns

The high resolution data from the automatic measurement equipment is used to identify temporal patterns in nutrient concentrations in the water (Figure 6). The automatic measurements are complemented by weekly grab samples that are filtered and frozen and sent to the lab at JLU Giessen for analysis for NO_3-N, total dissolved nitrogen (TDN) and DOC. The nitrate data is used to check the nitrate measurements made by the automatic equipment. The DOC data is used to check the automatic measurements as well, but the DOC measured with the ion chromatograph in the lab is a slightly different DOC fraction compared to the DOC measured with the *in-situ* spectrometer. The TDN data is used to investigate differences in TDN composition (inorganic vs organic dissolved nitrogen) throughout the year as well as between catchments with different land use.

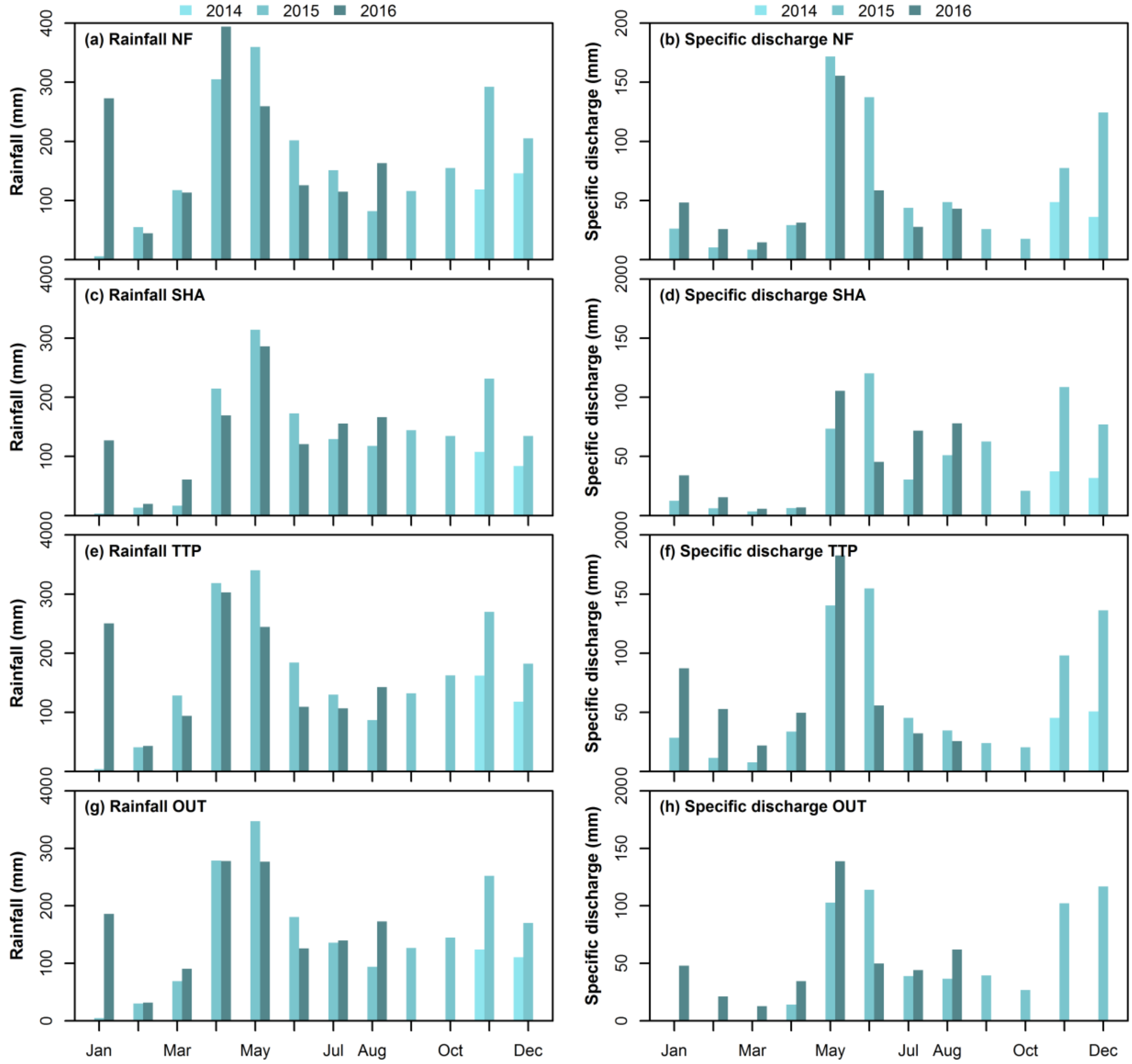

Figure 5 Comparison of monthly rainfall and specific discharge for (a,b) NF – natural forest, (c,d) SHA – smallholder agriculture, (e,f) TTP – tea/tree plantations and (g,h) OUT – main outlet for November 2014 to August 2016.

There is a quite clear difference between nitrate concentrations in the three sub-catchments, with highest concentrations found in the tea/tree plantations and lowest in the natural forest. Response of NO_3-N concentrations to rainfall seems different in the forest compared to the tea and smallholder agriculture. It seems less responsive, showing only large peaks after the long dry season of 2015, whereas nitrate concentrations increase steadily after the onset of the rains in the tea and smallholder catchments. Nitrate concentrations at the main outlet reflect a combination of the concentrations observed in the three sub-catchments. DOC concentrations often show a peak during rainfall events, although there seems to be a dilution effect as well in the tea and smallholder catchments at the peak discharge of a storm event. As mentioned before, long-term trends observed in DOC concentrations, especially in the natural forest, should be interpreted with care due to the biofouling issue.

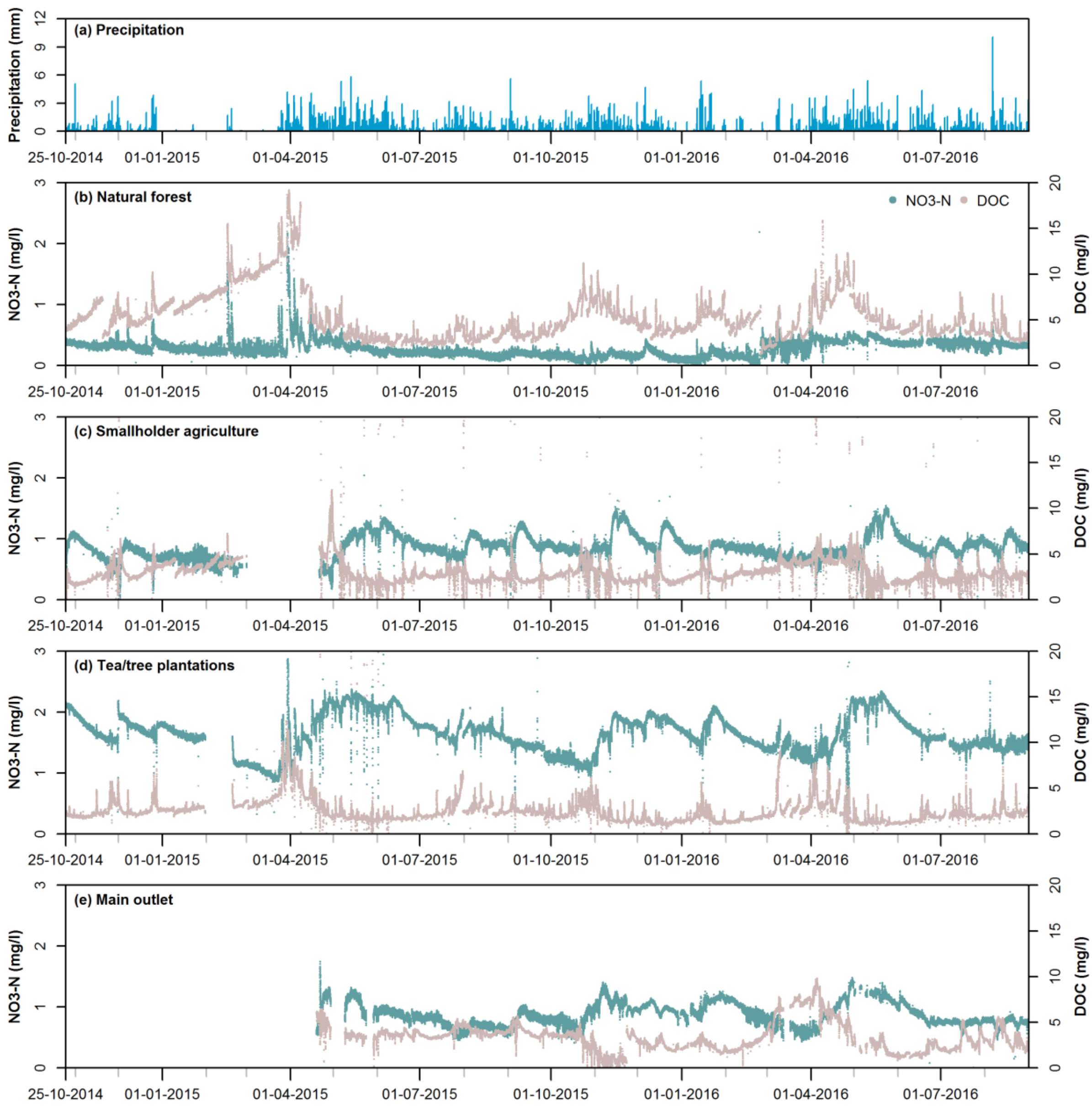

Figure 6 (a) Rainfall in the study area, and nitrate and dissolved organic carbon concentrations in the (b) natural forest, (c) smallholder agriculture, (d) tea/tree plantations and (e) main outlet.

3.2.2 *Response to rainfall*

The high-resolution data allows for comparison of concentration-discharge dynamics during rainfall events, also called hysteresis analysis. For selected rainfall events in 2015, concentrations of nitrate and DOC are plotted against discharge (Figure 7). Each rainfall event is indicated in a different colour, with the lighter shade of the colour indicating the start of the event and the darker shade the end of the event. These hysteresis patterns show how nitrate and DOC behave on the rising (increasing discharge) and falling (decreasing discharge) limb of the hydrograph during and after the rainfall event. If different patterns are observed between storm events or between the three catchments, this indicates that different processes play a role (Evans and Davies, 1998).

Both nitrate and DOC concentrations in the tea catchments show dilution (decrease in concentration) at the highest discharge of the selected storm events during the short and long rains, while concentrations in the natural forest stay more or less the same with even an increase in concentration at peak discharge during the event in the short rains. The patterns in the smallholder catchments are much less clear, although some dilution seems to occur for DOC. During the start of the long rains, both nitrate and DOC concentrations in the natural forest and tea plantations show a significant increase with increasing discharge, indicating increased export of these substances during the first rains after a long spell of dry weather.

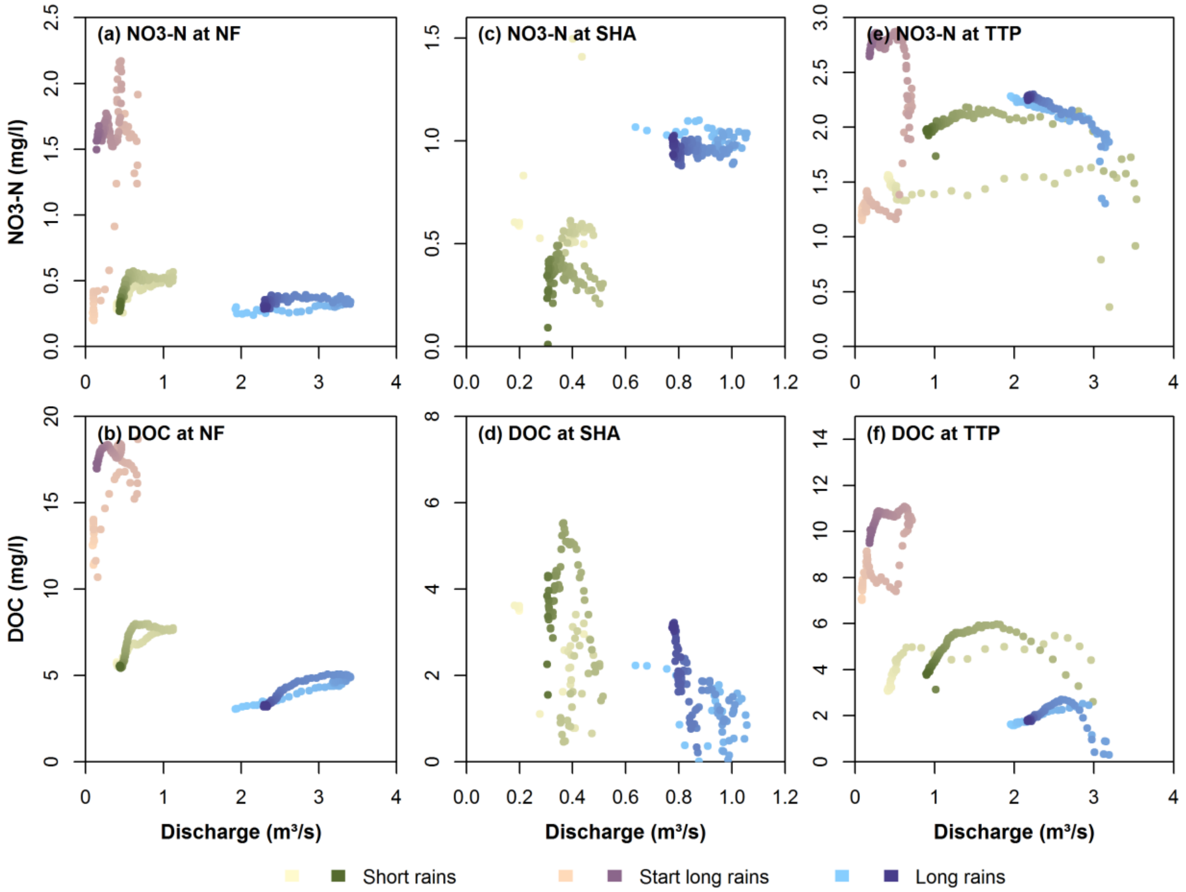

Figure 7 Hysteresis patterns (discharge vs. nitrate/DOC concentration) for three rainfall events, indicated with the different colours (see legend at bottom of graph), measured at 10 min interval, in the (a,b) NF – natural forest, (c,d) SHA – smallholder catchment and (e,f) TTP – tea/tree plantations. No data was available for SHA during the start of the long rains due to sensor malfunctioning. For each event, the lighter shade indicates the start of the rainfall event, the darker shade indicates the end.

4 Outlook and concluding remarks

The 22 months of data collected for the sub-catchments and sixteen months of data for the main catchment already give us an interesting insight in the water and nutrient dynamics in the South-West Mau area. However, because of the natural variability of the climate, as illustrated by the prolonged dry season and the very wet short rainy season of 2015, it will be necessary to collect data for a longer period to come to more reliable conclusions. Together with information obtained from analysis of trace element and stable isotope samples, a longer data set will give us the opportunity to increase our knowledge and understanding of water and nutrient cycling in this forested ecosystem. The data obtained from the automatic measurement systems will be publicly available after publication of scientific papers based on the data.

The project is expected to run for at least another two years, after which the monitoring systems will be relocated for scientific research in another country where CIFOR operates. During this period, the data will be used to assist in the development of a robust, low-cost monitoring strategy within the citizen science project with WRMA, GIZ and JLU Giessen, which can be applied on a larger scale, requires less maintenance, and is therefore more sustainable for long-term monitoring.

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Appendix 1 – Rating curve development

Regular discharge measurements are taken at the four measurement sites to cover a range of water levels, using the Acoustic Doppler Current Profiler (ADCP; RiverSurveyor S5, SonTek, San Diego CA, USA) at high water level, and the Acoustic Doppler Velocimeter (ADV; FlowTracker, SonTek, San Diego CA, USA) or the salt dilution method (Moore, 2004) at low water level. These measurements are used to develop a stage-discharge relationship or rating curve for each of the catchments (Figure A1), using a second order polynomial function:

$$Q = a + bh + ch^2 \tag{1}$$

where Q is discharge in m³/s, h is stage or water level in m and a, b and c are parameters to be estimated with the measured data.

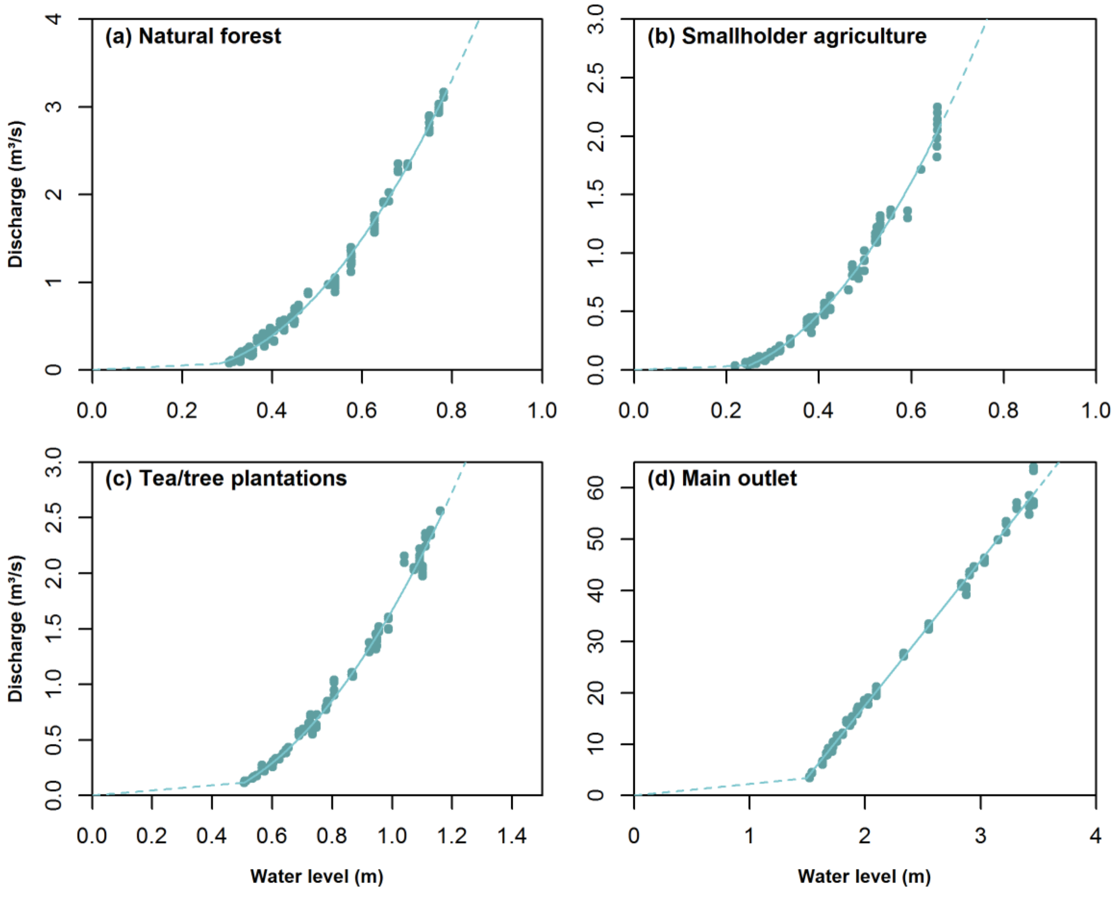

Figure A1 Rating curves or stage-discharge relationships for the estimation of discharge from water level measurements by the automatic equipment, for the four catchments.

Extrapolation between h_0, where $Q = 0$ m³/s, and the lowest water level for which a discharge measurement was carried out, is done with a linear equation:

$$Q = a(h - h_0) \tag{2}$$

where Q is discharge in m³/s, h is stage or water level, h_0 the water level for which $Q = 0$ and a is the slope, calculated using:

$$a = \frac{Q_{min}}{h_{min} - h_0} \tag{3}$$

where Q_{min} is the discharge measured at the h_{min}, lowest water level for which a discharge measurement was carried out. Equation (1) is used for extrapolation above h_{max}, the highest water level for which a discharge measurement was carried out, although care has to be taken with the interpretation of extrapolated discharge estimates. The rating curve equations are used to estimate discharge for the water level time series data from the automatic stations.

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