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Monitoring wetland cover changes during the past two decades within the protected areas of the Sudd wetland in South Sudan using MODIS data

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Charlotta Ruuskanen (2021).
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Undersökning av vegetationsförändringar inom Suddträskets naturskyddsområden i Sydsudan under de senaste två decennierna med hjälp av MODIS data

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Master thesis, 30 credits, in *Physical Geography and Ecosystem Science*

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Abstract

The Sudd wetland, situated along the White Nile in the Republic of South Sudan, is recognized internationally for its unique environmental features. The distinctive ecological characteristics have resulted in the creation of numerous nature reserves in efforts to conserve the habitats and ecosystem services provided. Monitoring changes within the nature reserves usually contributes to their protection. However, the political instabilities within the Republic of South Sudan makes obtaining in-situ data measurements difficult. Remote sensing technology therefore provides a solution to monitoring areas otherwise restricted by inaccessibility or regional conflicts.

The aim of this thesis project was to monitor potential wetland vegetation cover changes within the protected areas of the Sudd wetland in March 2000-2020. Possible variations in wetland cover were related to water level changes in Lake Victoria, Lake Albert, and Lake Kyoga, in addition to average precipitation from the years preceding the obtain wetland vegetation cover. Furthermore, frequency and magnitude of armed conflicts associated with herder-pastoralist communities surrounding the protected areas was related to changes in vegetation dynamics and the hydrological variables. The wetland vegetation cover was categorized into three groups, open water, seasonally-flooded grassland, and marsh, using previously reported classification methods of applying historical MODIS NDVI imagery data.

This thesis project found the water levels of Lake Albert to significantly influence the spatial and temporal variations in wetland vegetation cover extent, corresponding with previously reported results. Continued elevated water basins levels may have potentially sustained a high value of mean NDVI within the Sudd wetland during years of nationwide droughts. The water levels of Lake Victoria and Lake Kyoga, in addition to the average yearly precipitation appeared to have no statistically significant association with the mean NDVI and vegetation cover area of the Sudd wetland. This study found the yearly number of reported conflicts to be associated with an elevated mean NDVI, and to be predominantly distributed in close proximity to ethnic pastoral boarders and within larger cities and towns. No statistically significant correlation was found between the magnitude of conflicts and the vegetational and hydrological variables. The analysis further highlighted the spatial variations in vegetation covers between the protected areas of the Sudd wetland, indicating a high natural variability within the areas. Monitoring variations in vegetation cover as performed in this study contributes to our understanding how the wetland is affected by different mechanisms and processes over time. Furthermore, in a region expected to receive an increased frequency of climate extremes, the understanding of vegetation responses to hydrological fluctuations increases. The usage of satellite remote sensing for monitoring variations in wetland vegetation cover have in this thesis project shown to be an effective method for observing large inaccessible areas. Future studies should further focus on monitoring local changes within the wetland and their potential hydroclimatic drivers.

Sammanfattning

Suddträsket är ett internationellt erkänt våtmarksområde av stor betydelse som ligger beläget längst Vita Nilen i Sydsudan. Våtmarkens unika ekologiska miljöer har lett till skapandet av flera naturskyddsområden för bevarandet av de naturliga habitaten och dess ovärderliga ekosystemtjänster. Tillsyn av skyddsområdena bidrar i allmänhet till deras bevarande. Däremot har de pågående politiska osäkerheterna i Sydsudan begränsat tillgängligheten och därav försvårat tillsynsarbete och vidare forskning. Satellitbaserad fjärranalys bidrar med en lösning till undersökning av områden annars begränsade av regionala konflikter.

Syftet med studien var att undersöka potentiella variationer i våtmarksvegetationen inom Suddträskets naturskyddsområden under mars månad 2000–2020. Variationer i våtmarksvegetationen jämfördes med genomsnittliga vattennivåer i Victoriasjön, Albertsjön och Kyogasjön, samt variationer i genomsnittlig nederbörd. Därutöver undersöktes även förekomsten och omfattningen av konflikter associerade med pastorala samhällen omkring Suddträskets naturskyddsområden. Antalet rapporterade konflikter jämfördes med våtmarksvegetationen inom naturskyddsområdena samt de genomsnittliga värdena av de undersökta vattennivåerna och den årliga nederbörden. Våtmarksvegetationen kategoriserades i tre olika grupper, öppet vatten, översvämmade gräsmarker samt träsk, och baserades på tidigare klassificeringsmetoder med användning av MODIS NDVI satellitdata.

Masteruppsatsens analys fann att de hydrologiska variationerna i Albertsjön signifikant påverkade variationerna i vegetationsklassernas utbredd inom Suddträskets naturskyddsområden. Resultaten stämde överens med tidigare rapporterade studier. De genomsnittliga vattennivåerna kan potentiellt ha medfört fortsatt höga NDVI värden inom våtmarken under år med dokumenterad nationell torka. Däremot visade sig variationer i Victoriasjön, Kyogasjön samt genomsnittlig årlig nederbörd inte ha någon statistiskt signifikant effekt på NDVI eller vegetationsklassernas utbredd. Ytterligare fann analysen att antalet dokumenterade konflikter var associerade med ett högre värde av NDVI, samt att konflikterna var fördelade främst omkring större städer och i närheten av folkslagsspecifika pastorala gränser. Inga statistiskt signifikanta korrelationer hittades däremot mellan omfattningen av de dokumenterade konflikterna och de hydrologiska variablerna samt våtmarksvegetationen. Studien framhävde även naturliga variationer inom vegetationsklassernas utbredd mellan Suddträskets olika naturskyddsområden. Undersökningar likt denna studie bidrar till förståelsen hur olika mekanismer och processer påverkar våtmarksområdet under en längre tid. I ett område som förväntas utsättas för en ökad förekomst av klimatextrema händelser ökar behovet för förståelse kring vegetationsförändringar till följd av hydrologiska variationer. Användningen av satellitbaserad fjärranalys för undersökning av våtmarksvegetationer har i den här masteruppsats visat sig vara en effektiv metod. Framtida studier bör undersöka lokala vegetationsvariationer inom våtmarksområdet och deras potentiella hydroklimatologiska påverkningar.

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1. Introduction

Wetlands are considered one of the most important environmental resources in the world, providing ecosystem services of supportive, provisioning, regulating, and cultural significance (Langan et al, 2019; Millennium Ecosystem Assessment, 2005). The Sudd wetland, situated in the Republic of South Sudan, represent one of the largest freshwater ecosystems in the world and is recognized internationally for its unique ecological features (WHC, 2021). The wetland´s swamps, marshes and rain-fed grasslands supports various of endangered mammalian species, palearctic migratory birds, and fish populations (WHC, 2021; UNDP, 2007). The abundance of wildlife in the Sudd wetland have resulted in the creation of numerous reserves in efforts to protect and conserve the unique habitats. Currently, the wetland is protected by the Shambe National Park (620 km^2) established in 1985, and the Ez Zeraf (8000 km^2) and Fanyikang Game Reserve (480 km^2) established in 1939. Additionally, an area of 57,000 km^2 was recognized in 2006 as a Ramsar Site of International Importance, making the Sudd wetland the world´s fifth largest Ramsar Site (RSIS, 2021; UNEP-WCMC, 2021). Proposals to further extend the protection of the habitats have been made by the State Party of South Sudan by nominating the wetland for consideration as an UNESCO World Heritage site (WHC, 2021). However, despite the efforts of preserving the wetlands, the protected areas lack implementation of management plans for conserving the unique habitats and the sustainable usage of natural resources by indigenous communities inhabiting the Sudd.

The wetland vegetation and the ecosystem services provided is highly dependent on the hydrological regime (Sutcliffe, 1974). Sustained by an inflow of water by the Bahr el Jebel, also known as the White Nile, the water originating from Lake Victoria passes through Lake Kyoga and Lake Albert before reaching the Sudd wetlands. Seasonal fluctuations of the White Nile and precipitation patterns sustains a high diversity of plant species within the wetland, which can be categorized into five general vegetation cover categories; open water vegetation, permanent swamp, river flooded grassland, rain flooded grasslands, and floodplain scrubland (Soliman and Soussa, 2011; Petersen et al, 2007). The grasslands become seasonally inundated during the wet season, and functions as important grazing grounds during the dry season when little palatable grasses are available elsewhere (Sutcliffe, 1974; Soliman and Soussa, 2011).

The unique habitats of the Sudd wetland provide several important ecosystem services, including but not limited to water purification, flood control, carbon sequestration, fish and wildlife habitats, and year-round grazing grounds for livestock of indigenous pastoral cultures (WHC, 2021 Langan et al, 2019; Tsyganskaya et al, 2018; Sosnowski et al, 2016). The Sudd is primarily inhabited by three groups of pastoral people, which includes the Dinka, Nuer, and Shilluk. The Dinka and Nuer people seasonally migrate with up to a million livestock to their permanent settlements in the highlands when the river rises and seasonal floods inundate the region during the early rains in April

(Sosnowski et al, 2016; UNDP 2007; Sutcliffe 1974). During the dry season, lasting from December to March, people migrate back towards the previously flooded grasslands in search for new grazing grounds and water (Sosnowski et al, 2016). Resource-based conflicts over palatable grasslands and freshwater between the pastoral groups are not uncommon, and research suggests that conflicts associated with competition over natural resources might be aggravated by hydroclimatic variations (Maystadt et al, 2014; Tiitmamer et al, 2018; Ajak 2018).

The climate in South Sudan is characterized by seasons of heavy rains and drought. However, ongoing climatic changes have disrupted the seasonal patterns and exacerbated natural occurrences of seasonal events (UNEP, 2018; USAID, 2019; Ajak, 2018). Erratic rainfalls and prolonged dry periods have become more frequent, resulting in unpredicted and hazardous events of seasonal flooding and droughts (UNEP, 2018; Ajak, 2018). Protecting natural habitats and their ecosystem services becomes increasingly important as anthropogenic disturbances such as land use changes and furthermore climate extremes intensify. Monitoring changes within natural habitats usually contributes to their protection but is often limited by the availability of data, funding, and logistical concerns (Tsyganskaya et al, 2018; Sosnowski et al, 2016). Furthermore, area size, inaccessibility and regional instabilities further limits the capability to monitor natural habitats, but the need for scientific assessment merely increases in regions of conflicts (Sosnowski et al, 2016). The most recently performed scientific ground survey of the vegetation composition within the Sudd wetland was conducted between 1979-1981 by the Range Ecology Survey (Di Vittorio and Georgakakos, 2018; El Moghraby et al, 2006). However, more recently conducted monitoring of the Sudd wetland has been made possible by the usage of satellite imagery data (Di Vittorio and Georgakakos, 2018; Sosnowski et al, 2016). Remote sensing technology provides a solution to monitoring of large areas otherwise restricted by inaccessibility or regional conflicts. Today, archives of remotely sensed data dates back several decades. These historical data records make it possible to monitor changes over a longer period of time, which in turn, can provide information to help us better understand how ecosystems are affected by different mechanisms and processes over time, and furthermore provide useful information for the development and implementation of conservation management plans of unique habitats such as the Sudd wetland.

2. Aim

The aim of this thesis study is to monitor potential wetland vegetation cover changes during the end of the dry season in March month throughout the past two decades within the protected areas of the Sudd wetland, situated in the Republic of South Sudan. Possible variations in vegetation cover will be related to the preceding wet season water levels within the three main lakes sustaining the White Nile (Lake Victoria, Lake Kyoga, and Lake Albert), in addition to changes in annual precipitation patterns during the previous years. The frequency and magnitude of armed conflicts associated with herder-pastoralist communities surrounding the Sudd wetland during the dry season will furthermore be related to changes in wetland cover dynamics and the hydrological drivers. The hypothesises of this thesis project are, (1) the wetland vegetation covers of March month displaying yearly differences within the protected areas. Furthermore, (2) higher water levels in Lake Victoria, Lake Kyoga and Lake Albert will result in an increase of mean NDVI in addition to an increase of marsh cover within the study area. Lastly, (3) the frequency and magnitude of reported conflicts will increase as the availability of natural resources decline, which will be observed through a lower value of mean NDVI and lower values of the hydrological variables.

The objectives will be met by answering the following research questions:

I. Have the mean NDVI and wetland vegetation covers of March month varied temporally and spatially within the study area among the years of 2000-2020?
II. Are there any statistically significant relationships between mean precipitation and lake water levels with obtained wetland vegetation cover area and mean NDVI within the study area?
III. Are there any statistically significant relationships between the frequency and magnitude of conflicts surrounding the study area and the wetland vegetation cover area and mean NDVI within the study area, as well as lake water levels and mean precipitation?

3. Background

3.1 Ecological features

A great number of wildlife species are reliant on the wetland and its habitats, especially during the dry season when much of the surrounding areas of the Sahel region are experiencing drought (Sutcliffe, 1974; WHC, 2021). Notable wildlife species inhabiting the Sudd wetlands includes the African elephant (*Loxodonta africana)*, the endemic Nile lechwe (*Kobus megaceros*) and sitatunga (*Tragelaphus spekii)*, African buffalo (*Syncerus caffer)*, hippopotamus (*Hippopotamus amphibius)*, and the migratory antelope species of white-eared kob (*Kobus kob thimasi)* and tiang (*Damaliscus lunatus tiang)* (WHC, 2021). The great migration of the white-eared kob and tiang represents one of the largest ungulate migrations in the world (Morjam et al., 2017), moving over a million of animals across the plains of South Sudan in a seasonal search for new grazing grounds (UNDP, 2007). Furthermore, the wetland provides important wintering grounds for many migratory birds such as the black tern (*Chlidonias niger*), white stork (*Ciconia ciconi*), and the great white pelican (*Pelecanus onocrotalus*) (WHC, 2021). The four protective areas covering the Sudd wetland include different habitat varieties and have separate management objectives (figure 1). Shambe National Park, mostly consisting of flooded savannahs and riverine scrublands, is protected for its natural biodiversity and underlying ecological structure and environmental processes (ICUN, 2021).

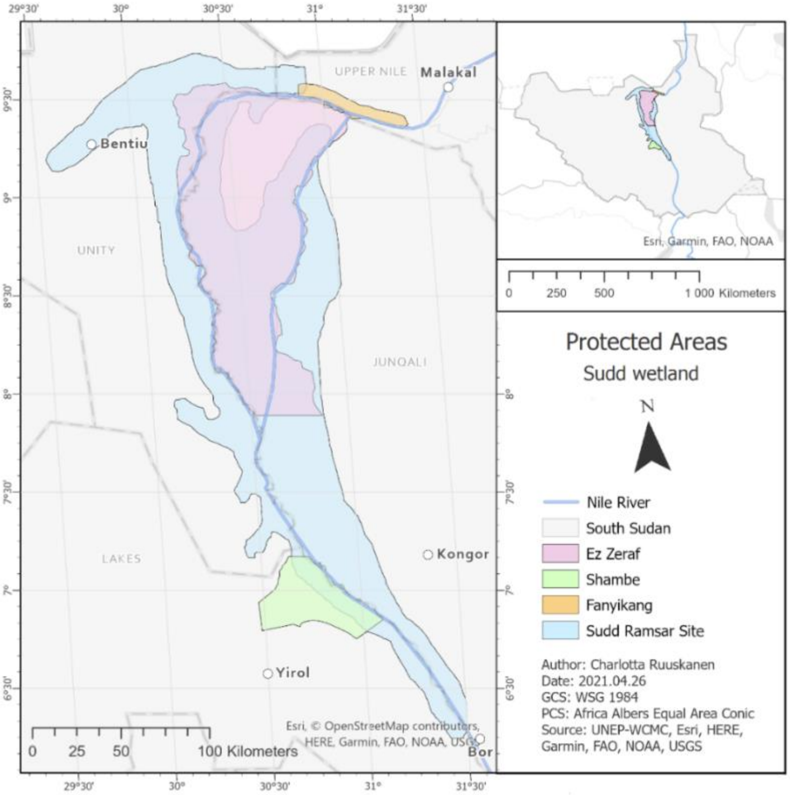

Figure 1: The four protective areas cover the Sudd wetlands; Sudd Ramsar Site (blue), Ez Zeraf Game Reserve (pink), Shambe National Park (green) and Fanyikang Game Reserve (orange).

Ez Zeraf and Fanyikang Game Reserve are both primarily habitats of flooded grasslands and are protected for the conservation of their natural ecosystems combined with the associated traditional practices of sustainable resource management (ICUN, 2021). Once a former sanctuary for the northern white rhinoceros (*Ceratotherium simum cottoni)*, Shambe National Park is today inhabited by vulnerable species such as the critical endangered Nubian giraffe (*Giraffa camelopardalis camelopardalis*). Furthermore, Ez Zeraf Game Reserve is the primarily refuge for the endangered endemic Nile lechwe (Ministry of Environment and Forestry, 2019). However, the ongoing political instabilities makes implementing management plans for conservation difficult. Despite the national and international efforts of preserving the wetlands, the Sudd and its unique wildlife are endangered by wildlife poaching, pastoralist-induced burning and overgrazing, crop clearance, oil exploration and extraction, as well as climate change (UNDP, 2007). The wetland would furthermore be threatened by the potential resumption of the Jonglei canal, a channel project designed to by-pass water from the Sudd region in order to increase the amount of water further downstream the Nile River (Di Vittotio and Georgakakos 2018; UNDP, 2007).

3.2 Hydrological regime

The Sudd wetlands is formed by the White Nile in a flat topographic area between the towns Bor and Malakal and sustained by an inflow of water originating from Lake Victoria (figure 2; UNDP, 2021). The extent of the Sudd wetland is highly variable, ranging between 42,000 km^2 during the dry season to 90,000 km^2 in the rainy season (WHC, 2021). The variability of the wetland extent is dependent on fluctuations of river discharge in addition to rainfall runoff (Soliman and Soussa, 2011; WHC, 2021). The annual movement of the Inter-Tropical Convergence Zone brings on the rainy season, usually extending from late April to November with a seasonal peak in July/August (Soliman and Soussa, 2011; UNEP, 2018). The rainfall is however variable in both time and place, and average annual precipitation observations around the wetland varies between 1000 mm/yr in the southwest to 600 mm/yr in the northeast (UNEP, 2018). The air temperature in the region ranges between 25-40°C and reaches its warmest period at the end of the dry season in March/April, and gradually decreases during the rainy season (Soliman and Soussa, 2011; UNEP, 2018).

Evapotranspiration over the Sudd wetland is extensive, and sometimes considered a waste of important water resources along the Nile River. Less than 45% of the incoming water of the White Nile exits the downstream end of the wetland as a result of the high evapotranspiration rates (Sosnowski et al, 2016; Mohamed and Savenije, 2014). As a part of an extensive series of proposed water conservation projects, the Jonglei canal was designed to divert water around the Sudd wetland to reduce the evaporation losses and increase water supply further downstream the Nile River in Sudan and Egypt (Sosnowski et al, 2016; Soliman and Soussa, 2011; Howell et al, 1988). The construction of the Jonglei canal project began in 1978 but was later on haltered by the onset of the Seconded Sudanese Civil War in the 1984 (Di Vittorio and Georgakakos, 2018; Sosnowski et al, 2016).

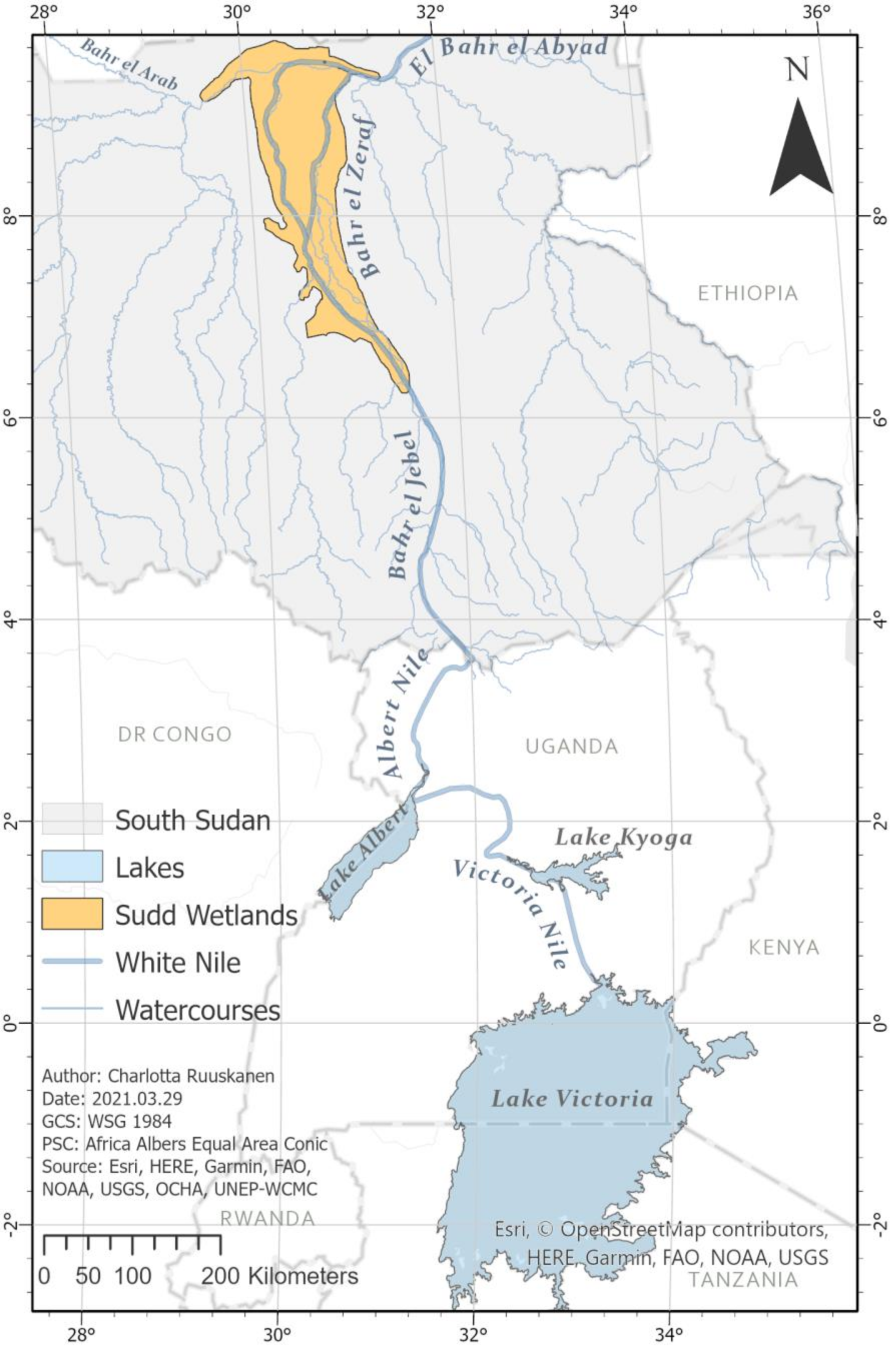

Figure 2: The rivers included in the White Nile; Victoria Nile, Albert Nile, Bahr el Jebel, Bahr el Zeraf and El Bahr el Abyad. In addition to other watercourses in South Sudan such as Bahr el Arab. The three main lakes sustaining the White Nile includes Lake Victoria, Lake Kyoga, and Lake Albert

The Jonglei canal remain uncompleted, and the environmental impact of the finished canal is a controversial topic as changes to the hydrological system would reduce the seasonal river flow of the wet and dry season by approximately 20% and 10% respectively, thereby impacting the ecological functions and ecosystem services of the wetland (RSIS, 2021; Langan et al, 2019; Soliman and Soussa, 2011; Sutcliffe, 1974).

3.3 Wetland vegetation

The wetland vegetation is highly dependent on the hydrological regime, and the species composition and biomass of the vegetation types are typically distributed in accordance with soil type and the degree of inundation (Sutcliffe, 1974). The vegetation composition within the five vegetation classes; open water vegetation, permanent swamp, river flooded grassland, rain flooded grasslands, and floodplain scrubland, varies seasonally. Generally, permanent swamps occur on permanently inundated land and is mainly inhabited by *Cyperus papyrus*, and the grass species *Typha domingensis* and *Vossia cuspidate*. The river-flooded grasslands are mainly dominated by the large grass *Echinochloa pyramidalis* and the wild rice *Oryza longistaminata*, whereas the *Hyparrhenia rufa* and *Sporobolus pyramidalis* covers the rain-fed grasslands (Soliman and Soussa, 2011; Petersen et al, 2007). These grasslands, especially the river-fed pastures, become seasonally inundated during the wet season and provides important grazing grounds during the drier months (Sosnowski et al, 2016). Furthermore, the floodplain scrublands are mainly dominated by different grasses and the tree species *Acacia seyal* and *Acacia sieberiana*. Due to the vegetation cover being situated further from the riverbanks in comparison to the grass plains, the floodplain scrublands are rain-sustained and well drained areas surrounding the marshes, making it possible for large tree species to grow. The floodplain scrublands are an important ecological zone for settlements, crop production, and wet season grazing when much of the grasslands remain flooded. Lastly, the open water vegetation refers to free-floating-leaved plants such as *Eichhornia crassipes* and *Lemna gibba* that may inhabit open water areas (Soliman and Soussa, 2011).

3.4 Pastoral Cultures

Livestock plays a central part in pastoralist cultures, serving as a key function in the economic and social systems of pastoral societies. Cattle herd size is often considered as a reliable indicator of wealth and social status, and is used as compensation for wrongdoings, gifts, and furthermore bridewealth required in marriage arrangements (Wild et al, 2018; International Crisis Group, 2011). Cattle raiding and associated conflicts are a longstanding historical feature of many pastoralist societies (Wild et al, 2018). However, due to the widespread acquisitions of arms, raiding practices have become more violent among ethnic pastoral groups, causing significant concern for nomadic communities (International Crisis Group, 2011). The livestock practices of pastoral societies are entirely dependent on the seasonal flooding of the Sudd wetlands for providing enough palatable grazing grounds to sustain the cattle during the dry season (Howell et al, 1988; Soliman and Soussa, 2011). It is not uncommon for conflicts to emerge within grazing territories (International Crisis Group, 2011). Some research suggests that conflicts associated with competition over natural resources might be aggravated by variations in the hydrological regime and regional climate (Maystadt et al, 2014; Tiitmamer et al, 2018; Ajak 2018), increasing the need for scientific assessment to understand and furthermore predict vegetational and hydrological changes within the wetland.

3.5 Monitoring wetland greenness

Normalized Difference Vegetation Index (NDVI; Rouse et al. 1974) is a remote sensing descriptor often used as an indicator of vegetation density (g m^{-2}) and overall plant greenness. The spectral optical properties of vegetation are controlled by the physical characteristics of leaves, including cell structure, lignin and cellulose substance, water content, and the concentration of pigments, mostly chlorophyll (Ustin, 2020). Green vegetation has a low reflectance in the red electromagnetic region (0.4 - 0.7 µm), due to leaf pigments absorbing visible light energy for use in photosynthesis. Contrarily, green vegetation has a higher reflectance in the near infrared (NIR) electromagnetic region (0.7 - 2.5 µm), as a result of the cell structures strongly reflecting light energy in the NIR spectrum (Earth Observatory, 2021). NDVI uses the spectral properties of vegetation for providing values indicating the vegetation greenness of an observed area on a scale from -1.0 to 1.0.

$$(\mathrm{NDVI} = \frac{\mathrm{NIR} - \mathrm{Red}}{\mathrm{NIR} + \mathrm{Red}})$$

Even though NDVI is not a direct measurement of the physical properties of a vegetation cover, the obtained spectral reflectance in the red and NIR wavelengths makes it useful in ecosystem monitoring (Copernicus, 2021). Higher values of NDVI reveals areas of denser and more chlorophyll concentrated vegetation, whereas lower values of NDVI corresponds to areas with little or no vegetation (Sosnowski et al, 2016). The vegetation index has been widely used to monitor and characterize biomass of wetland vegetation cover (Sosnowski et al, 2016, Chen et al, 2014, Landmann et al, 2010, Di Vittorio and Georgakakos, 2018). The index is especially suitable for monitoring wetland vegetation in arid environmental conditions since the restricted growth of biomass keeps the index from being oversaturated, in addition to its ability of distinguish between wet and dry environments (Adam et al, 2010; Sosnowski et al, 2016). The Moderate Resolution Imaging Spectroradiometer (MODIS) instrument on the Terra MODIS and Aqua MODIS satellites gather global spectral information of the Earth’s surface every 1 to 2 days within the spectral wavelengths of 0.4 µm to 14.4 µm (NASA, 2021). Additionally, the developed Terra MODIS Vegetation Indices (MOD13Q1) contains computed 16-days NDVI averages from atmospherically corrected bi-directional surfaces reflectance at a 250 m spatial resolution. The MODIS NDVI product (MOD13Q1 version 6) are furthermore masked for water, clouds, cloud shadows, and heavy aerosols, and the algorithm applied selects the best available pixel values from all the acquisitions dates during the 16-day retrieval period (LP DAAC, 2021; Ladsweb, 2021).

A spatial resolution of 250 m is suitable for monitoring larger regional areas. Similarly, the 16-day data composites are favourable as daily collected imagery data are more adversely affected by cloud cover and atmospheric interference (Sosnowski et al, 2016). However, monitoring wetlands through the usage of satellite imagery data also presents its challenges. Wetlands are highly dynamic ecosystems and are not unified by one specific landcover feature (Gallant, 2015). Additionally, the Sudd also experiences high seasonal changes in wetland extent, making it difficult to delineate the actual wetland boundary (Sosnowski et al, 2016). Previous studies such as Sosnowski et al (2016) and Di Vittorio and Georgakakos (2018) have used MODIS NDVI imagery data to monitor vegetation cover changes within the Sudd wetland. When remotely observing wetland cover dynamics using MODIS NDVI products, the vegetation cover classes needs be rather extensive due to the moderate spatial resolution (Sosnowski et al, 2016).

The Sudd wetland vegetation classification performed by Sosnowski et al (2016) was originally used on semi-arid wetlands in western Burkina Faso and southern Mali by Landmann et al (2010). The classification used the MODIS NDVI values to create statistical thresholds for characterizing the wetland vegetation classes. In the study by Sosnowski et al (2016) a thermally derived boundary of the Sudd wetland was monitored during the early and mid-dry season (December-February) between 2000-2014 and the wetland was categorized into three statistically derived wetland cover classes instead of the original six classes used by Landman et al (2010). The intentionally broad wetland cover classes included open water, seasonally-flooded grassland, and regularly-flooded grassland or marshes. The class of open water had low values of NDVI and indicated areas of little or no vegetation, representing open water extents. Regularly-flooded grasslands were permanent swamps and marshes with high values of NDVI as the vegetation growth was unrestricted due to having a large supply of freshwater and a high amount of solar radiation. Seasonally-flooded grassland had moderate NDVI values and the vegetation was less robust than the marsh cover class due to not being permanently inundated (Sosnowski et al, 2016). Seasonally-flooded grassland represented the river and rain fed grasslands as well as the floodplain scrublands.

4. Methodology

4.1 Study Area

The study area of this thesis project was defined to include the four protected areas covering the Sudd wetland, situated in South Sudan (figure 3). Previous studies have observed the Sudd wetland boundaries to extend beyond the protected areas (Sosnowski et al, 2016). However, delineating the exact boundary of the wetland remains a challenging task with the usage of optical remote sensing. Conflicting definitions on wetland boundaries, high seasonal and annual variability, and large quantities of freely floating vegetation makes it difficult to outline exact wetland boundaries (Tsyganskaya et al, 2018; Gallant, 2015; Yin and Lu, 2006). Therefore, the study area of this master thesis was limited to cover the Sudd Ramsar Site, Ez Zeraf Game Reserve, Shambe National Park, and Fanyikang Game Reserve, and furthermore centre around the changes in wetland cover dynamics within these accredited areas of national and international importance. Administrative boundaries for the protected areas were obtained from the UN Environment World Conservation Monitoring Center (UNEP-

WCMC, 2021). The study area was used when monitoring changes in wetland cover classes during March month within the protected areas, and additional boundaries were set when obtaining the average precipitation data (figure 3).

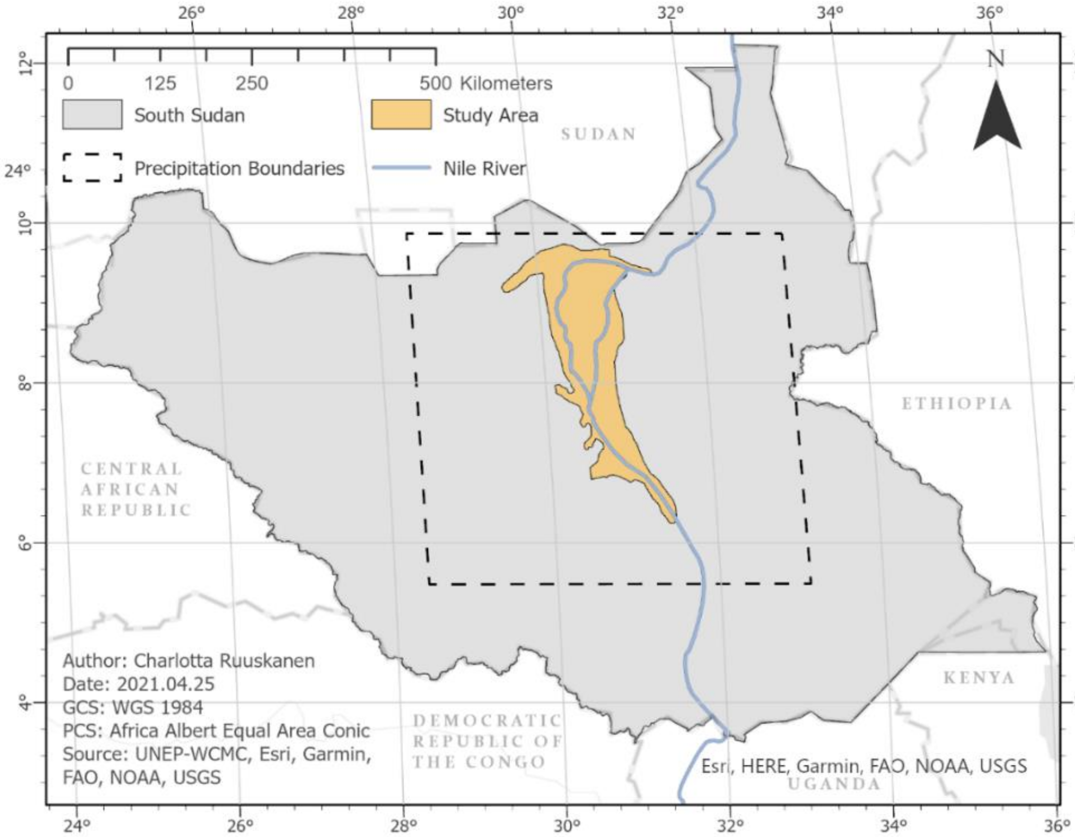

Figure 3: The study area and precipitation boundaries used in the thesis project to study wetland cover classes and impacts of seasonal precipitation means.

4.2 Study Period

The thesis project was defined to include the dry season during 2000-2020. Due to optical remote sensing data being limited by atmospheric disturbances (Gallant, 2015), remote satellite observations during the dry season are preferable as it limits the interference of cloud covers otherwise present during the rainier months. The NDVI imagery data in this study was limited to only include values obtained at the end of the dry season in March month, adding to previous studies by Sosnowski et al (2016) monitoring the wetland during the early and mid-dry season in December-February during 2000-2014.

4.3 Data

The data products used in this thesis project included MODIS NDVI imagery, hydrological imagery and altimetry data and armed conflict information (table 1).

Table 1: The data, specification and source of the products used in the thesis project.

Data	Specification	Source
NDVI imagery data	MOD13Q1.006 Terra Vegetation Indices 16-Day Global 250 m. Date: March (DOY: 65 and 81) 2000 – 2020.	LP DAAC (2021)
Validation NDVI imagery data	Landsat 7 Collection 1 Tier 1 8-Day NDVI Composite. Spatial resolution: 30 m. Date: 2010.03.06, 2010.03.14, 2010.03.22, 2010.03.30.	USGS & NASA (2021)
Lake level heights	Satellite altimetry data of Lake Victoria, Lake Albert, and Lake Kyoga. Date: December-March 1999 – 2020.	Hydroweb (2021)
Precipitation imagery data	Monthly Global Precipitation Measurement (GPM) v6. Spatial resolution: 0.1 arc degrees. Date: May-March 2000 – 2020	NASA GES DISC (Huffman et al, 2019)
Armed Conflict data	Herder-Pastoralist conflicts in South Sudan (2011 – 2020), and Sudan (2000 – 2010). Date: December-March 2000-2020	ACLED (2021)

4.4 Methodology of wetland cover classification

Atmospherically corrected MODIS 250m NDVI data (MOD13Q1) was retrieved using the AppEEARS webtool (Didan 2015; AppEEARS Team 2020). Imagery data of the two 16-day composites obtained in March (day 65 and 81 of the year (DOY)) from year 2000-2020 was extracted, making a total of 42 NDVI images covering the study site of the four protected areas (figure 4). The wetland cover was divided into three classes, previously defined and reported by Landmann et al (2010) and Sosnowski et al (2016). The wetland cover classes included, open water (OW), seasonally-flooded grassland (SFG), and marsh (M), and was derived from the mean March NDVI values. In line with Sosnowski et al (2016) any pixels containing a NDVI value below two standard deviations under the calculated mean was categorized as open water. Likewise, pixels with NDVI values above one standard deviation over the calculated mean was categorized as marsh. Pixel values between the classes of open water and marshland was categorized as seasonally flooded grassland. Statistical thresholds were calculated separately for the 21 yearly images. Since the study by Sosnowski et al (2016) also performed a wetland cover classification, but over an extended part of the Sudd wetland during the early to mid-dry season, a comparison of results was considered beneficial to the study.

4.5 Validation and accuracy assessment

The evaluation of wetland vegetation cover classification through the usage of high-resolution (30 m) Landsat imagery data have successfully been performed in previous studies in the case of missing ground control data (Han and Niu, 2020; Sosnowski et al, 2016; Chen et al, 2014; Landman et al, 2010). A Landsat 7 Collection 1 Tier 1 mean NDVI 8-day composites of March 2010 were obtained using Google Earth Engine. The mean average was calculated from imagery obtained in between 2010.03.01 - 2010.03.31. The obtained data was already atmospherically corrected by calibrated top-of-atmosphere reflectance. Statistical thresholds for the 2010 imagery were calculated and a wetland cover classification computed as performed for the MODIS NDVI wetland cover classification.

For the validation of the wetland cover classification, a total of 500 accuracy assessment points were generated, 167 in each wetland cover class, using as stratified random sampling strategy to ensure sample points within all the wetland covers. However, 98 sample points were located within a no data area in the Landsat image, leaving the number of sampling points per class to; OW: 129, SFG: 135, and M: 139. With the sample points, a confusion matrix of the MODIS NDVI data and the reference Landsat 7 NDVI data was computed.

4.6 Influences of hydrological drivers

To uncover whether wetland cover dynamics within the protected areas are related to variations in chosen hydrological variables during the wet season prior to the NDVI data, satellite derived altimetry data for Lake Victoria, Lake Albert, and Lake Kyoga during 1999-2019 was obtained using the Hydroweb tool. The obtained timeseries specifying the height above surface of reference (HASR; GGMO2C; high resolution global gravity model) were specified by LEGOS (Laboratoire d'Etude en Géophysique et Océanographie Spatialeand) and computed by CLS (Collecte Localisation Satellites) in Toulouse, France. Monthly values of height above surface (m) were extracted for each lake to create yearly wet season (April-November) means for each lake during 1999/2000-2019. The temporal range was used to account for the transportation of water to the wetland, in addition to observing lake level heights throughout its maximum water input during the wet season.

In addition to water levels of the three main lakes sustaining the White Nile, the impact of annual precipitation on the NDVI and wetland vegetation cover was examined by retrieving Monthly Global Precipitation Measurements v6 (Huffman et al., 2019) using Google Earth Engine. Due to the dry season receiving very little precipitation, precipitation means (mm/year) during 2000-2020 within the defined precipitation boundary (figure 3) were computed to contain yearly means of the precipitation the preceding year (April-March). The Monthly Global Precipitation Measurements began acquiring data in June 2000. Therefore, the average precipitation values used in this study included the years between 2001-2020. The precipitation boundary was used to account for possible rainfall runoffs and potential flooding from surrounding watercourses.

4.7 Assessment of armed pastoral conflicts

Data of the reported number of conflicts and fatalities in South Sudan (2011-2020) and Sudan (2000-2010) were obtained from ACLED (The Armed Conflict Location and Event Data Project). The number of armed conflicts were filtered to only include reported herder-pastoralist conflicts within 30 km of the study area during the dry season (December-March). The boundary was extended to include areas outside of the protected areas as too few conflicts were reported within the study area for any statistical analysis to be performed. Additionally, the vegetation cover was assumed to be similar within a boundary of 30 km of the protected areas as previous studies observing the Sudd have delineated the wetland boundary to be extending outside of the protected area boundaries (Sosnowski et al, 2016). The keywords used to filter the armed conflicts to only contain disputes associated with herder-pastoralists included cattle, cow, raid, pastoralist, and herders.

4.8 Data Analysis and Statistical Testing

ArcGIS Pro 2.6.0 were used to prepare, analyse, and visually present the data and results. Statistical testing was performed using RStudio 1.4.1106, and graphs were produced in both Excel 2104 and RStudio 1.4.1106.

The wetland vegetation cover areas (km^2), mean NDVI, lake level heights (m), mean precipitation (mm/year), number of conflicts, and number of fatalities during 2000-2020 were checked for normal distribution using Shapiro-Wilks´ test of normality, with a chosen alpha value of 0.05 (Shapiro and Wilk, 1965). Possible statistical relationship between the variables were tested using either a Pearson’s Correlation test (Pearson, 1895), or Kendall Rank Correlation Coefficient (Kendall, 1938) depending on the distribution of the datasets.

5. Results

5.1 Wetland cover dynamics within the protected areas

The yearly mean NDVI of March month, derived from the two 16-day composites (DOY 65 and 81) between 2000-2020, displays annual changes of mean NDVI within the study area. The annual threshold values determining the OW pixels (lower error bars) and M pixels (upper error bars) furthermore highlights annual variabilities of the wetland (figure 4). The mean NDVI ranges from a minimum of 0.345 in March 2010 to a maximum 0.463 in March 2014.

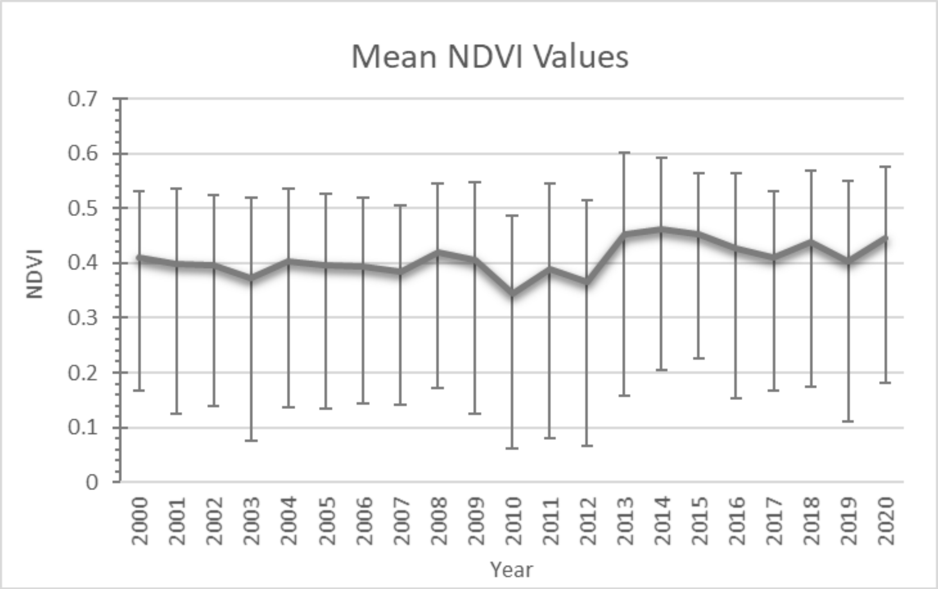

Figure 4: The mean NDVI of March month and the statistical thresholds for open water (lower error bars) and marsh (upper error bars) within the study area during 2000-2020. Pixel (250m x250m) count for each yearly image is 533966.

The calculated statistical thresholds for determining the three wetland cover classes; OW, SFG, and M, calculated separately for each year are displayed in the appendix: table A1. Comparable values of statistical thresholds of NDVI when determining the three wetland cover classes have been reported by Landmann et al (2010) and Sosnowski et al (2016) (table 2).

Table 2: The mean value of the calculated statistical thresholds during March 2000-2020 for the three different wetland cover classes, and the reported calculated thresholds in other scientific articles.

Class	**Calculated mean thresholds**	**Reported mean thresholds***
Open water (OW)	(≤) 0.14 (0.1-0.18)	(0.14-0.24)
Seasonally flooded grassland (SFG)	0.34 (0.27-0.39)	0.36 (0.24-0.44)
Marsh (M)	(≥) 0.54 (0.49-60)	(≥) 0.44

* Landmann et al 2010; Sosnowski et al 2016.

The calculated mean NDVI for March and the derived wetland cover classes based on the computed statistical thresholds (appendix: table A1) for the minimum mean NDVI 2010 and the maximum mean NDVI 2014 are displayed in figure 5. As shown in the histogram displaying the distribution of NDVI (figure 6), the distribution of the pixels in 2010 are skewed towards lower values of NDVI whereas the distribution in 2014 are skewed towards higher values of NDVI. However, the M cover appears to have a higher density during 2010 in comparison with 2014 (figure 5). When comparing the distribution of NDVI with the calculated statistical thresholds for each year (appendix: table A1), most of the pixels in 2010 are within the range of the SFG class (NDVI 0.07-0.48) and very few pixels have an NDVI below the OW class value of 0.06. Similarly, the pixel distribution in 2014 were mostly within the range of the SFG class (NDVI

0.21-0.58; appendix: table A1), however, more pixels are found below the OW class threshold of 0.20.

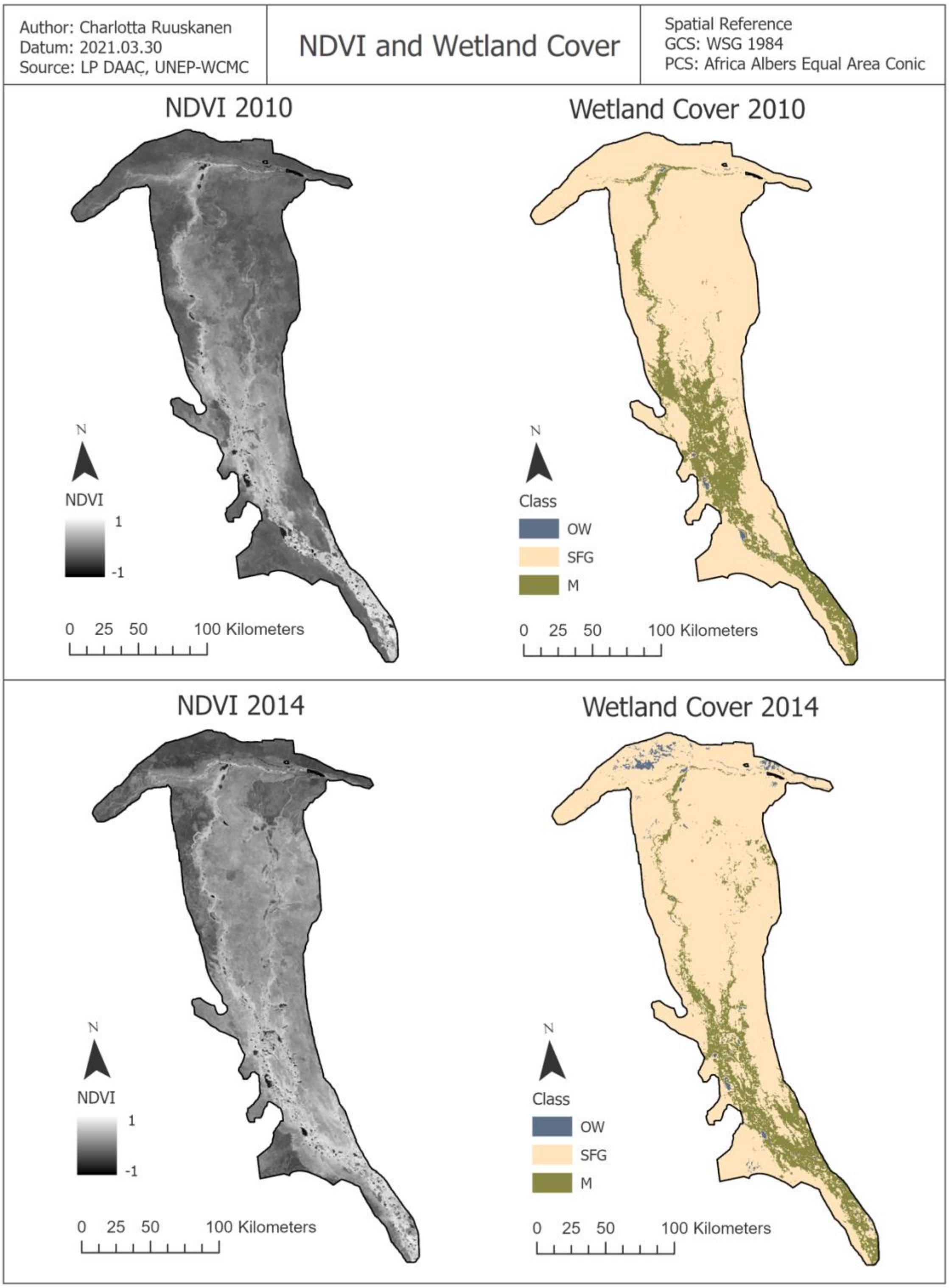

Figure 5: The NDVI and wetland cover classes; open water (OW), seasonally-flooded grassland (SFG) and marsh (M), within the study area in March 2010 and March 2014.

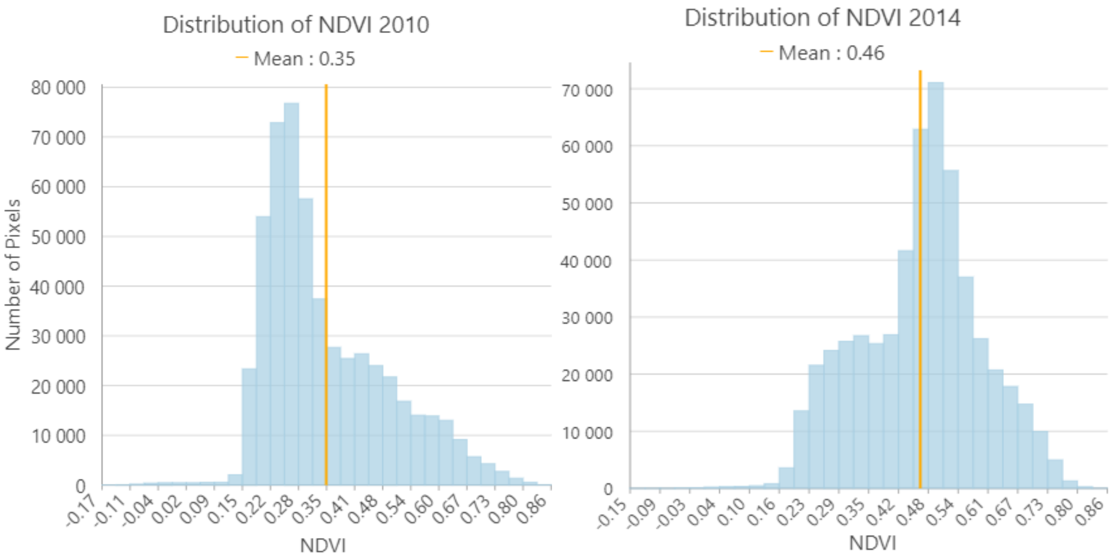

Figure 6: Distribution of NDVI within the study area during March 2010 and March 2014. The mean NDVI of 2010 and 2014 is 0.35 and 0.46, respectively.

The dynamics of the wetland covers ratios (figure 7; figure 8) based on the calculated statistical thresholds and additional wetland cover maps during the full study period 2000-2020 (appendix figure A2) further highlights the vegetation variability within the study area. The wetland cover area dynamics (%) within the study area in March during 2000-2020 shows that the dominant wetland cover is SFG throughout the study period, with an area coverage ranging between 80-84%. Whereas the OW cover and M cover had an area coverage varying between 0.2-2.5% and 14-19% respectively (figure 7).

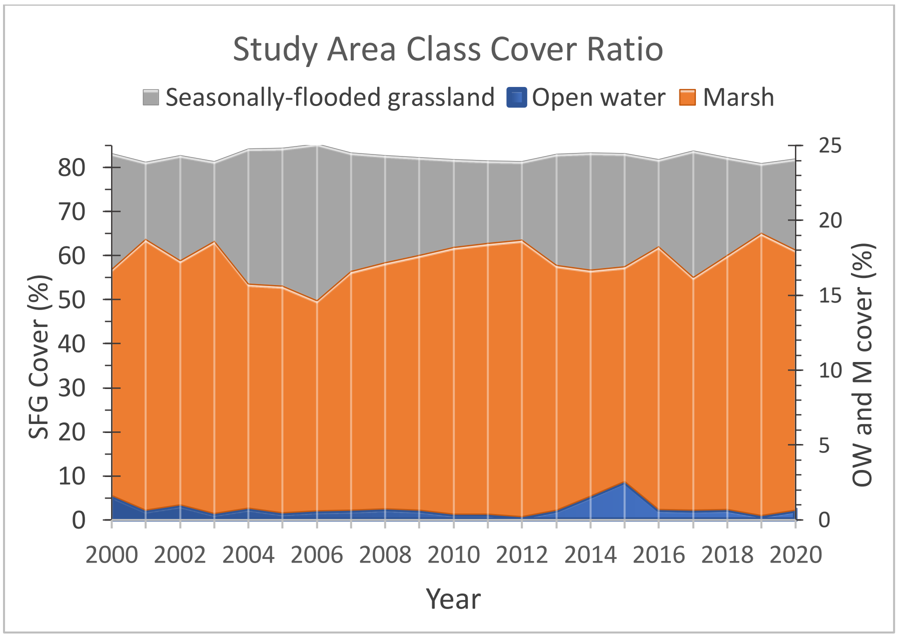

Figure 7: Variations in wetland cover (%) within the complete study area (66100 km^2) during March 2000-2020. Seasonally-flooded grassland cover (grey) is displayed on the y-axis, and open water (blue) in addition to marsh (orange) covers are displayed on the z-axis.

Years with a higher amount of OW appears to be in accordance with a higher mean NDVI, as seen for year 2014 and 2015 (figure 4). Similarly, years with a lower mean NDVI seemed to have a decrease in OW cover, as displayed during 2003, 2010, and 2012. Furthermore, the M cover increase appears to be fluctuating in accordance with an overall OW cover and mean NDVI decline. This implies that a high value of mean NDVI is associated with higher number of pixels within the OW class, and a lower pixel count within the M class (figure 7).

Wetland cover dynamics within the four protective areas covering the Sudd wetland are displayed in figure 8; Sudd Ramsar Site (figure 8a), Ez Zeraf Game Reserve (figure 8b), Shambe National Park (figure 8c) and Fanyikang Game Reserve (figure 8d). The protected areas experience different annual variations in wetland cover dynamics.

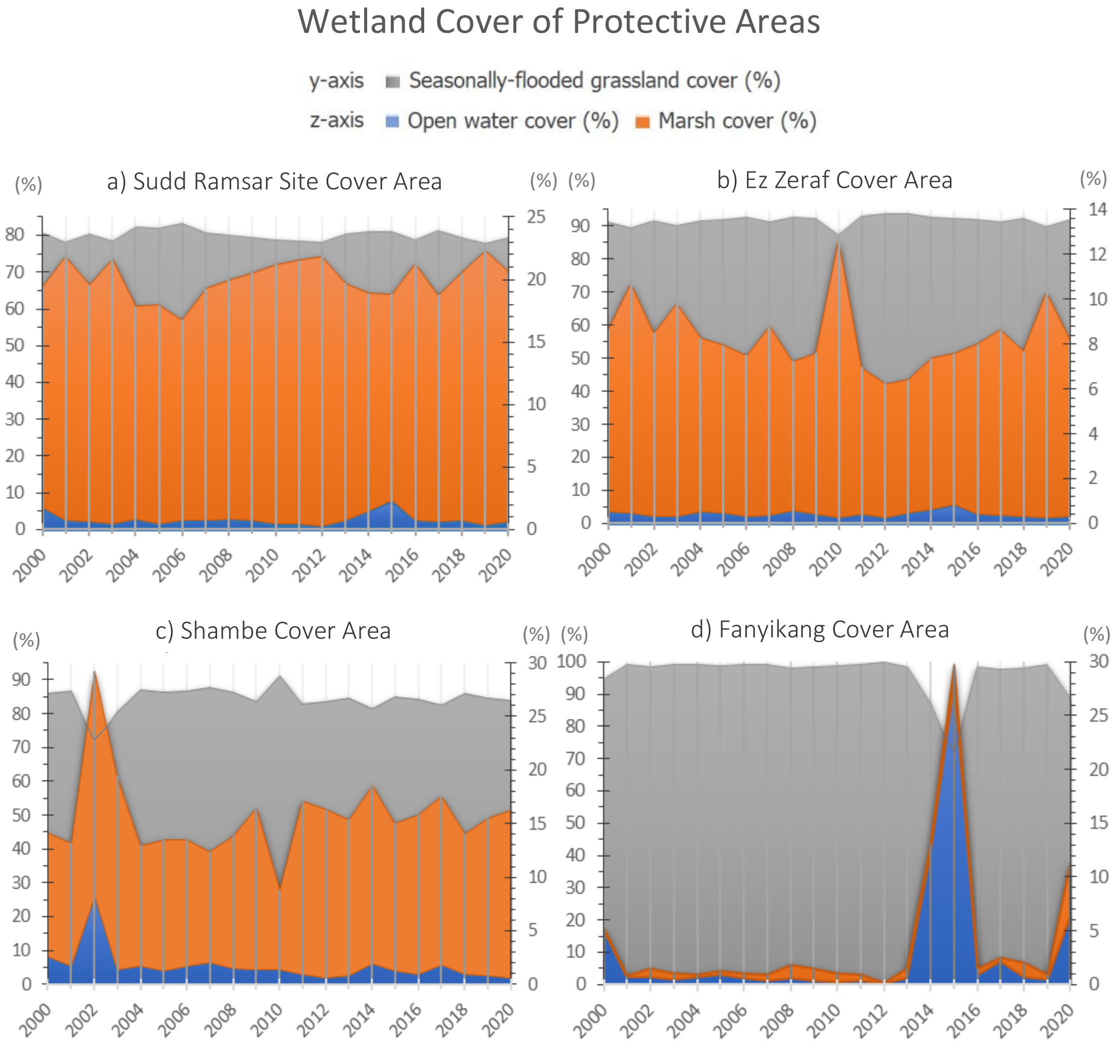

Figure 8: Variations in wetland cover area in km2 (y-axis) during March 2000-2020 (x-axis) within (a) Sudd Ramsar Site, (b) Ez Zeraf Game Reserve, (c) Shambe National Park, and (d) Fanyikang Game Reserve. Open water (blue), marsh (orange) and seasonally-flooded grassland (grey) displays the calculated monthly mean statistical thresholds.

Since the Sudd Ramsar site (figure 8a) has the largest area and covers most of the study site, the wetland cover dynamics area similar to the variations within the full study area (figure 7). Shambe (figure 8c) and Fanyikang (figure 8d) have the highest variations in wetland cover during March 2000-2020 but are also the smallest protected areas meaning that the variations are rather local. All of the protected areas had the highest wetland vegetation cover of SFG class, ranging between 70-99% of the total vegetation cover. Ez Zeraf Game Reserve (figure 8b) appears to have the lowest count of OW cover in relation to area size.

5.2 Validation and accuracy assessment of the wetland cover

The evaluation of the wetland cover classifications is displayed in a confusion matrix (table 3). The overall accuracy of the classification indicated that 72% of the reference sites were correctly classified. Furthermore, the overall kappa index implied that the mapped wetland cover were 58% better than chance agreement. These accuracy metrics are however initial evaluations of the performance and may disguise key differences between the three wetland classes. For instance, user´s accuracy of both SFG and M were relatively high, with values of 96% and 81% respectively, indicating a good chance of random points on the map being correctly categorized. However, the user´s accuracy of OW did not perform as well with a value of 38%. The producer´s accuracy was the highest for OW with a 100% followed by M with a 94%, meaning that 100% and 94% of the OW and M on the reference Landsat 7 map has been assigned the correct class. However, the producer´s accuracy for SFG only had an accuracy value of 55%, indicating that 45% of the SFG on the reference map were assigned inaccurately.

Table 3: Confusion matrix of the wetland cover classes; OW (129 sampling points), SFG (135 sampling points), and M (139 sampling points).

Confusion Matrix			
Accuracy Assessment (%)	**Open water (OW)**	**Seasonally-flooded grassland (SFG)**	**Marsh (M)**
Overall Accuracy	72		
Overall Kappa	58		
Individual Kappa	100	33	91
User Accuracy	38	96	81
Producer Accuracy	100	55	94

5.3 The impact of hydrological drivers on wetland cover distribution

The obtained statistically significant relationships between the lake levels heights during the previous wet season and mean NDVI, and wetland cover classes within the study area are shown in table 4. There was a statistically significant relationship between the lake level heights of Lake Albert and the SFG cover extent (figure 9; Pearson´s Correlation, PPC: 0.57, p-value: 0.01), with the correlation having a large strength of association.

Table 4: The statistically significant relationships found between the lake levels during the previous wet season (April-November), and the wetland cover distribution and mean NDVI, using Pearson´s Correlation Coefficient test.

Correlation between Lake Levels and mean NDVI, and Wetland Cover Distribution		
Analysis Performed	**p-value**	**Pearsons Correlation Coefficient**
Lake Albert Levels (m) *x* *SFG area (km^2)*	0.01	0.57
Lake Albert Levels (m) *x* *M area (km^2)*	0.03	-0.47

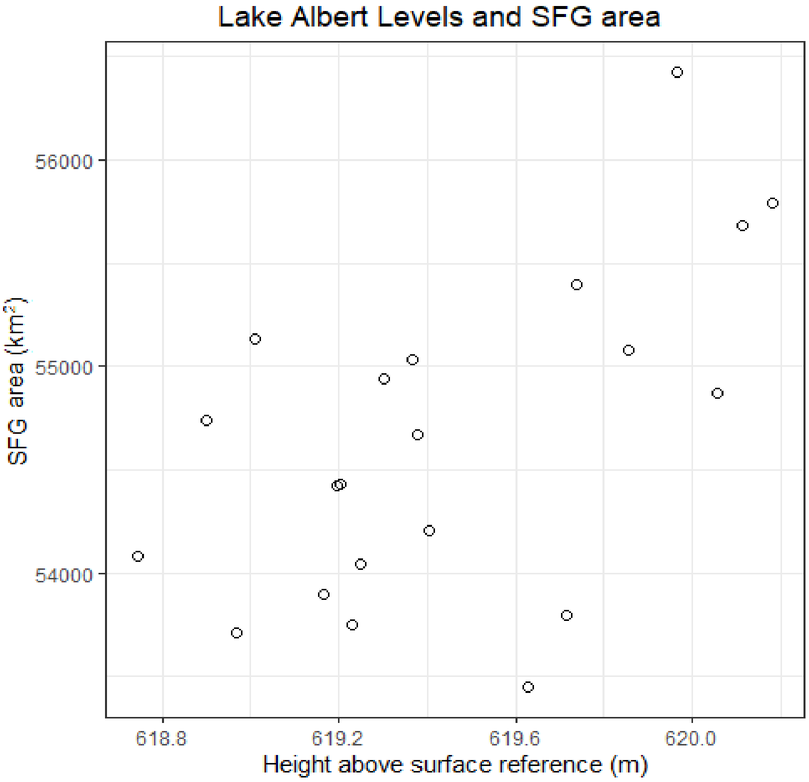

Figure 9: A scatterplot displaying the statistical correlation between Lake Albert water levels in height above surface reference (m) during the wet season and SFG area (km^2) of March month within the study area during 2000-2020. (Pearson´s Correlation, PPC: 0.57, p-value: 0.01).

Furthermore, there were a statistically significant relationship between the wet season lake level heights of Lake Albert and the M cover area (figure 10; Pearson´s Correlation, PPC: -0.47 p-value: 0.03), having a moderate strength of association.

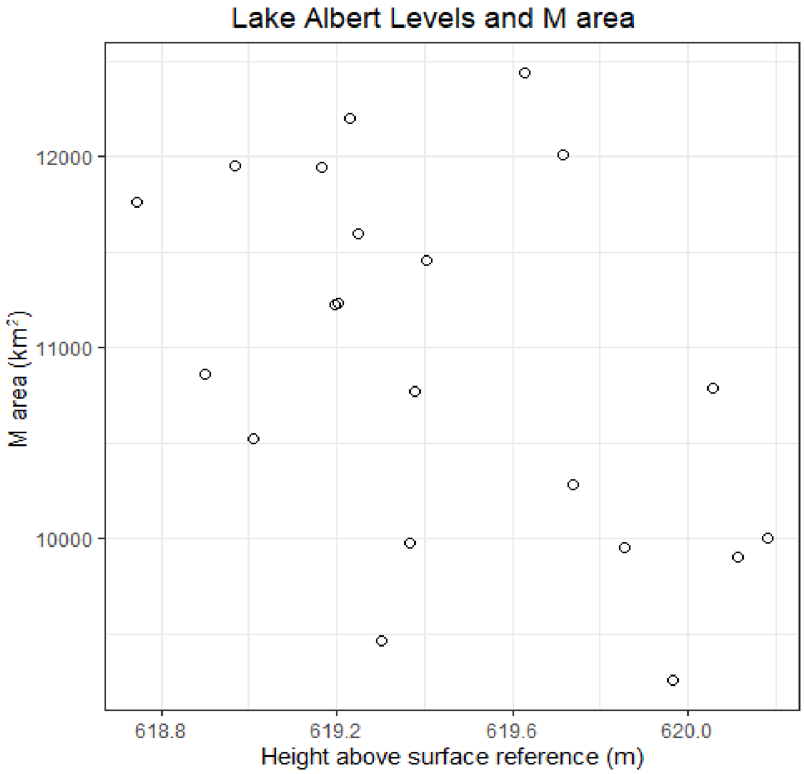

Figure 10: A scatterplot displaying the statistical correlation between Lake Albert water levels in height above surface reference (m) during the wet season and M area (km^2) of March month within the study area during 2000-2020. (Pearson´s Correlation, PPC: -0.47, p-value: 0.03).

The correlations suggest that the area of SFG and M are related to the mean lake level height of Lake Albert during the previous wet season (April-November). Furthermore, the correlations indicate that higher lake level heights during the wet season is associated with an increase in SFG area (figure 11) during the following dry season in addition to a decrease in M area (figure 12).

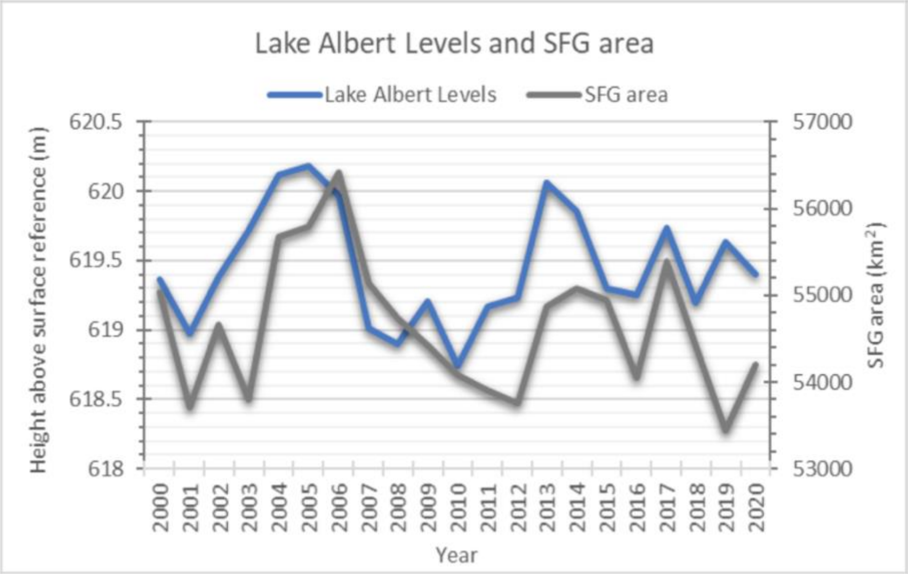

Figure 11: Lake Albert Levels in meters above surface reference during the previous wet season (blue) and SFG area of March month within the study area in km^2 (grey) during 2000-2020.

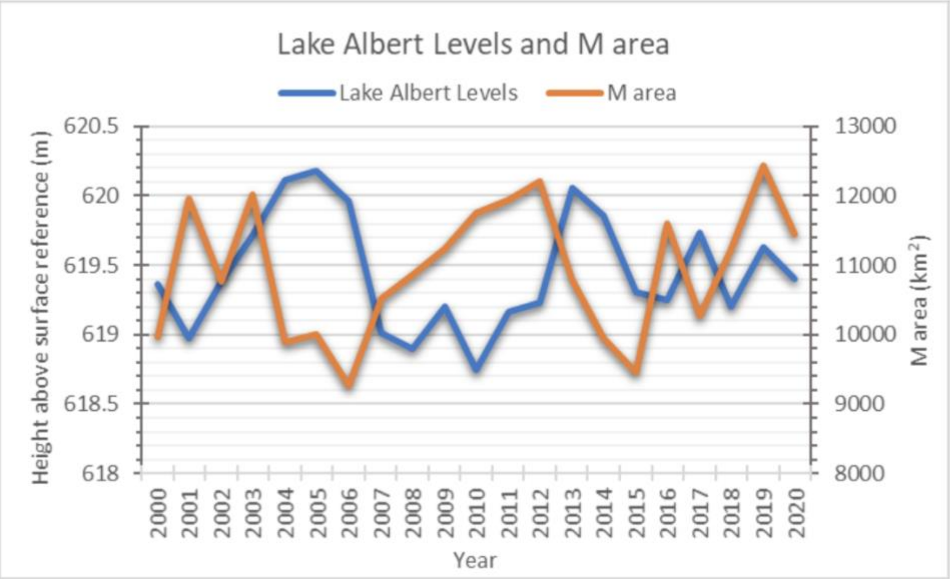

Figure 12: Lake Albert Levels in meters above surface reference during the previous wet season (blue) and M area of March month within the study area in km^2 (orange) during 2000-2020.

No statistical relationship was found when correlating the lake level heights of Lake Albert with the mean NDVI and OW cover area within the study area. Furthermore, no statistical relationship was found between the lake level hight of Lake Victoria and Lake Kyoga when correlating with the values of mean NDVI and wetland vegetation covers. However, the statistical analysis indicated a potential influence of the water levels of Lake Victoria on the mean NDVI of the study area, displaying a non-statistically significant correlation between the Lake Victoria levels and the mean NDVI (Pearson´s Correlation, PPC: 0.40, p-value: 0.07).

The tested statistical relationships between the mean precipitation the previous year (April-March) and the mean NDVI and wetland cover classes within the study area are shown in table 5. No statistically significant relationship was found between the mean precipitation values and the mean NDVI, and the wetland cover classes, suggesting that the average precipitation during the previous wet season within the used precipitations boundaries had no statistically significant influence on the obtained environmental variables.

Table 5: The statistical relationships tested between the precipitation previous year (April-March), and the wetland cover distribution, and mean NDVI. The correlations were performed using Pearson´s Correlation Coefficient test and Kendall´s Rank Correlation Coefficient.

Correlation between Precipitation and mean NDVI, and Wetland Cover Distribution			
Analysis Performed	**p-value**	**Correlation Coefficient**	**Correlation Test**
Precipitation Previous Year (mm) *x* *Mean NDVI of study area*	0.23	0.28	Pearson
Precipitation Previous Year (mm) *x* *OW area (km^2)*	0.08	0.28	Kendall
Precipitation Previous Year (mm) *x* *SFG area (km^2)*	0.89	0.03	Pearson
Precipitation Previous Year (mm) *x* *M area (km^2)*	0.60	-0.12	Pearson

5.4 Assessment of armed conflicts surrounding the protected areas

The number of documented herder-pastoralist conflicts and fatalities within 30 km of the study area during the dry season in 2000-2020 shows and increase of reported conflicts (figure 13). No herder-pastoralists conflicts were reported within 30 km of the area during the dry season in 2001-2004, 2006-2007.

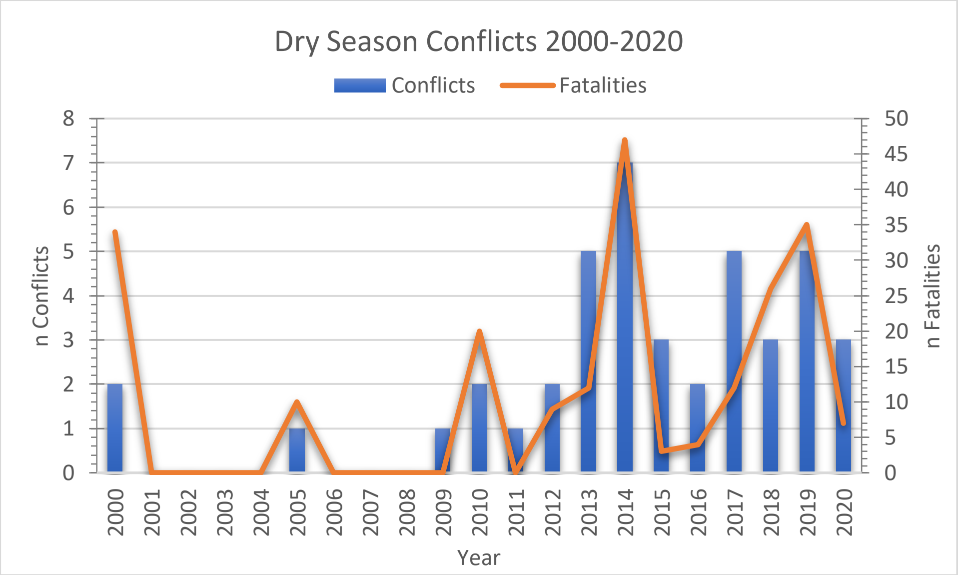

Figure 13: The number of reported herder-pastoralist conflicts and fatalities within a 30 km radius of the study area during the dry season (December–March) 2000-2020. There were no reported herder-pastoralist conflicts within the conflict area in 2001- 2004, and 2006-2008.

Since South Sudan's independence in 2011 the area surrounding the wetland have had a clear rise in armed conflicts. The dry season graph (figure 13) further illustrates the event of the South Sudanese Civil War in 2013-2014, with an increase in frequency and magnitude around the study area. The total amount of documented conflicts during 2000-2020 was 201 with a reported number of fatalities being 1464. Most conflicts were reported during the rainy season of May-November, having a number of 103 reported incidents and 863 reported casualties. During the dry season of December-March, a number of 42 conflicts were reported associated with herder-pastoralists, resulting in 216 casualties within the study period 2000-2020.

The reported conflicts during the dry season were mostly situated within the major cities and towns, with the Lake state capital Bor having the highest density of documented conflicts (figure 14). Furthermore, several conflicts appear to be reported in close proximity to the ethnic borders between the pastoral groups of Nuer, Dinka and Shilluk.

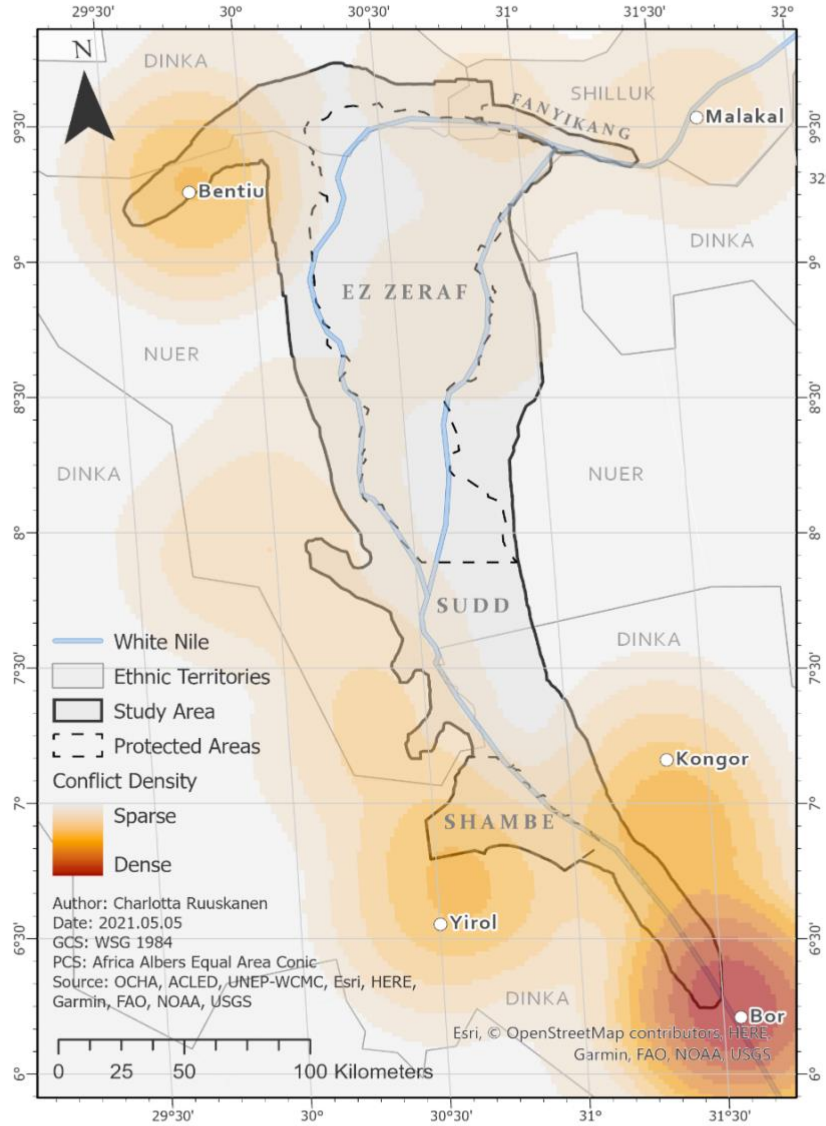

Figure 14: The distribution and density of armed conflicts associated with herder-pastoralist within 30 km of the study area during the dry season (December-March) between 2000-2020.

The tested statistical relationships, using Kendall´s Rank Correlation Coefficient, between the total number of documented herder-pastoralist conflicts during the dry season within 30 km of the protected areas, and the vegetational and hydrological variables are displayed in table 6.

Table 6: The statistical relationships tested between the number of reported herder-pastoralist conflicts during dry season (December-March) within 30 km of the protected areas, and the mean NDVI, wetland cover distribution, lake levels, and precipitation.

Correlation between number of Conflicts and mean NDVI, Wetland Cover Distribution, Lake Levels, and Precipitation, using Kendall´s Rank Correlation Coefficient		
Analysis Performed	**p-value**	**Tau Correlation Coefficient**
Number of Conflicts x Mean NDVI of study area	0.01	0.45
Number of Conflicts x OW area (km^2)	0.95	0.01
Number of Conflicts x SFG area (km^2)	0.85	-0.03
Number of Conflicts x M area (km^2)	0.95	-0.01
Number of Conflicts x Lake Victoria Levels (m)	0.07	0.30
Number of Conflicts x Lake Albert Levels (m)	0.17	0.23
Number of Conflicts x Lake Kyoga Levels (m)	0.21	-0.21
Number of Conflicts x Precipitation Previous Year (mm)	0.37	-0.16

During the dry season of study period 2000-2020 there was a statistically significant relationship between the number of documented conflicts and mean NDVI of the protected areas (figure 15; figure 16; Kendall´s Rank Correlation, Tau: 0.45, p-value: 0.01). The moderate strength of association between the variables suggest that the number of conflicts associated with pastoralist activities increased with an increasing value of NDVI.

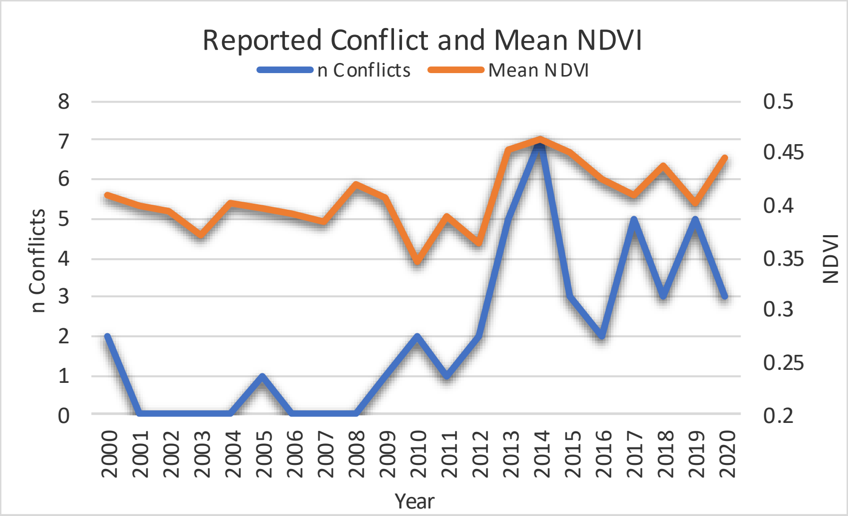

Figure 15: The number of armed conflicts associated with herder-pastoralists during December-March within 30 km of the study area (blue), and the obtained mean NDVI in March month (orange) within in the study area during 2000-2020.

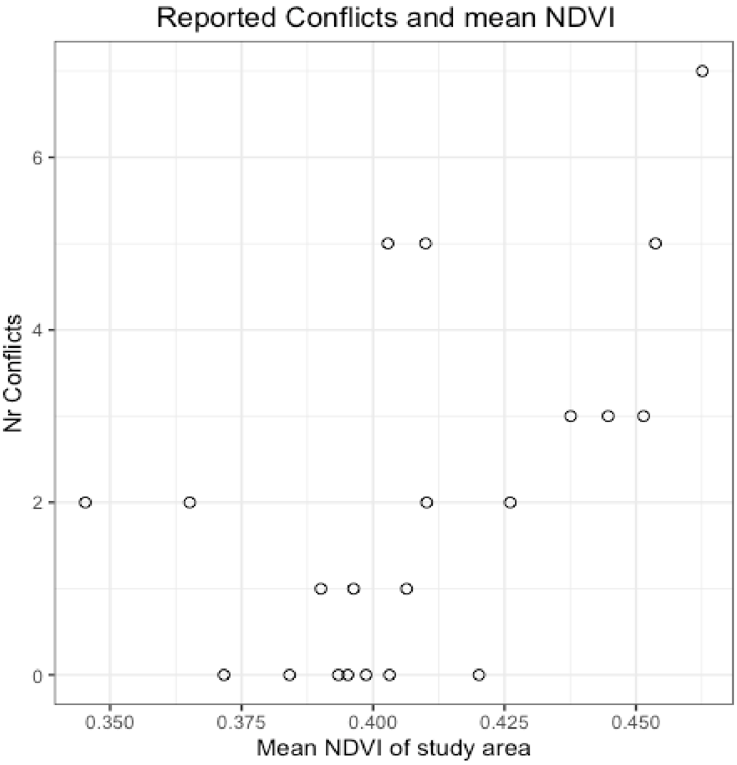

Figure 16: A scatterplot displaying the correlation between the number of armed conflicts associated with herder-pastoralists during December-March within 30 km of the study area, and the obtained mean NDVI in March month within in the study area during 2000-2020. (Kendall´s Rank Correlation, Tau: 0.45, p-value: 0.01).

Furthermore, neither the wetland cover distribution nor hydrological drivers showed any statistically significant relationship when correlated with the number of reported conflicts. The tested statistical relationship between the number of conflicts and water levels of Lake Victoria, Lake Albert and Lake Kyoga had a correlation coefficient with a fair to medium strength of association but displayed no statistical significance.

When analysing the potential relationships between the yearly number of reported fatalities associated with herder-pastoralist conflicts during the dry season within 30 km of the protected areas, and the vegetational and hydrological variables, no statistical relationships was found using Kendall´s Rank Correlation Coefficient. The analysis suggests that the severity of the conflicts was not statistically significantly related to the yearly changes of the environmental variables.

6. Discussion

6.1 Wetland cover dynamics and mean NDVI variations

6.1.1 Temporal variations in wetland vegetation cover

Annual variations of NDVI averages are expected in highly dynamic environments such as the Sudd wetland which experiences large seasonal and annual changes. The mean NDVI for the end of the dry season in March month varied both spatially and temporally within the protected areas during the full study period of 2000-2020, having a relatively low value of mean NDVI during 2010 and 2012, and a comparatively high value of mean NDVI during 2013-2015 (figure 4). Changes in mean NDVI are reflected in the wetland vegetation covers, resulting in the low NDVI period during 2010 and 2012 having very low values of OW cover. Furthermore, the years of a high mean NDVI also showed a higher value of OW cover (appendix: figure A2). These results are in accordance with previous studies monitoring the Sudd wetland, indicating the dry season of 2010 being exceptionally dry, whereas the dry season during 2014 instead being comparatively wet (Di Vittorio and Georgakakos, 2018; Sosnowski et al, 2016). Furthermore, foregoing observations displays a decrease in overall wetland extent during the dry season 2010, and contrastingly an overall wetland area increase during the dry season 2014 (Sosnowski et al, 2016). Within the full study area, SFG is shown to be the most extensive wetland vegetation cover accounting for roughly 80% of the area during the study period 2000-2020. Sosnowski et al (2016) similarly found the SFG class to be the most extensive wetland cover. Monitoring a larger area beyond the protected areas, Sosnowski et al (2016) found the SFG cover to account for more than 75% of the delineated wetland boundary. Within the combined areas of the nature reserves, the OW class accounted for roughly 1-2% of the study area, whereas the M class accounted for around 14-19%. Sosnowski et al (2016) found the OW cover and M cover during the early dry season 2000-2014 to make up 2-3% and 15-17% respectively. Thus, indicating that the additional area, beyond the nature reserves, used by Sosnowski et al (2016) were an extension of the wetland area.

6.1.2 Spatial variations in wetland vegetation cover

Since the Sudd Ramsar Site represents the largest protected areas within the Sudd wetland, the wetland cover dynamics within the Ramsar Site somewhat reflects the variations observed for the entire study area. Shambe National Park and Fanyikang Game Reserved had the most extensive wetland cover fluctuations, but also represents the smallest protected areas meaning that the vegetation cover dynamics within these nature reserves are local. During years not affected by severe droughts, Fanyikang consisted of a SFG cover extent accounting for more than 95% of the reserve. However, during the dry season of 2015, large parts of the nature reserve was flooded. Around 2200 km^2 were categorised as OW, accounting for roughly 28% of the total area. This extensive increase of OW cover during the dry season of 2015 was not observed at the same scale within the other reserves. The sudden increase of OW cover within the Fanyikang Game Reserve can be a result of an additional water inflow by the Bahr el Arab in the northern most parts of the Sudd wetland (figure 2). Similarly to Fanyikang, Shambe National Park appears to be a highly variable nature reserve with large fluctuations between the wetland vegetation covers. During the dry season of 2002, the national park received a notable increase in both OW cover and M cover, resulting in a decline in SFG. These large changes were not observed to the same extent within the more northern reserves, implying the changes were also rather local. Furthermore, the dry spell during 2010 appears to be rather prominent within Shambe National Park, resulting in the M cover area halving in size from its preceding year. Contrastingly, Ez Zeraf Game Reserve corresponded with an increase in M cover during the droughts of 2010, indicating a local rise of NDVI. Overall, Ez Zeraf does not display the same intense vegetation cover fluctuations as observed within Fanyikang and Shambe. Nonetheless, notable changes in vegetation cover were observed during the study period. The unique vegetational responses within the different nature reserves further highlights the spatial and temporal variations in NDVI, and consequently wetland vegetation cover, observed within the wetland during the study period of 2000-2020.

6.1.3 Accuracy assessment of the vegetation classification

The mean values of the statistical thresholds used to determine the three wetland vegetation cover classes showed somewhat similar values as previously reported thresholds by Landmann et al (2010) and Sosnowski et al (2016). The threshold values of OW cover was lower than the previously reported values, whereas the calculated threshold values for M cover was notably higher. Similarly, the threshold values of SFG cover had a smaller range than the values obtained by Landmann et al (2010) and Sosnowski et al (2016). Differences in the obtained mean NDVI thresholds can be explained by the spatial and temporal differences of the performed studies. Differences between the annual statistical thresholds are due to the thresholds being calculated separately for each yearly NDVI imagery. Because the wetland vegetation cover areas corresponded well with the values obtained in study presented by Sosnowski et al (2016), the methodology of wetland vegetation cover classification is presumed to have performed well in this thesis study. However, the validation of the wetland cover classification with the usage of Landsat 7 2010 imagery showed moderate values of overall accuracy and overall kappa index. These accuracy assessments are however initial evaluations of the results collectively, not accounting for key differences between the wetland cover classes. The probability of a random point on the wetland cover map in 2010 being correctly mapped had a high likelihood for the SFG and M covers, in comparison with the OW class were only 38% of all the areas that were classified during

2010 were actual OW cover. However, the likelihood of a random point of the reference wetland cover map in 2010 being correctly mapped had in turn a high probability for the OW and M cover, in comparison with a moderate likelihood for SFG cover. The individual kappa coefficients for the wetland vegetation classes in 2010 indicates a fair agreement for the SFG cover and a highly substantial agreement for OW cover and M cover. Implying that the wetland cover classification of SFG did not perform as well as the other two classes, having a 33% being better than change agreement. However, the period of 2010 was an exceptionally dry year as revealed by the values of mean NDVI and are therefore more representative of a NDVI anomaly than the general NDVI average. The accuracy assessment of the wetland cover classification might have been improved by assessing an additional year, in order to represent a more general wetland cover extent displayed during the study period of 2000-2020.

6.2 The impact of hydrological drivers on NDVI and wetland cover

The dry spell displayed by the mean NDVI (figure 4) and the local wetland vegetation cover changes (figure 7; appendix: figure A2) reflects the severe droughts observed across all Eastern Africa during 2010-2011 (Gebremeskel Haile et al, 2020). However, while most parts of South Sudan experienced severe droughts during the early months of 2015 and 2017 (Quinn et al, 2019; IPC, 2017), this does not seem to have affected the wetland´s mean NDVI and OW cover in the same extent as during the dry spell in 2010 (appendix: figure A2). The ability of the Sudd wetland to withstand national events of severe droughts could possibly be explained by the lake level heights of the main basins sustaining the White Nile. The wet season preceding the years of 2015 and 2017, when most parts of South Sudan experienced serious droughts, the water levels of Lake Victoria and Lake Albert remained relatively high. Similarly, during the dry spell of 2010, the water levels of the basins during the earlier wet season were considerably lower. The Sudd wetland appears to withstand intense national dry spells if the water inflow, originating from the water basins, remains stable. Thus, indicating the greenness of the Sudd wetland might be more affected by the incoming water levels than national climatic anomalies.

6.2.1 Influences by Lake Albert

The hydrological influences on the Sudd wetland are furthermore supported by the strong significant relationship between the Lake Albert water levels and the wetland vegetation covers extent of SFG and M. An increase in lake level heights would suggest an increased flooding of the White Nile, and further possibly result in a higher amount of OW and M vegetation. However, the statistical analysis indicated higher Lake Albert water levels during the wet season being associated with an overall increase in SFG area and a decrease in M area during the following dry season. The decreased amount of incoming water due to lower lake levels could further result in a slower moving waterflow allowing for the domination of marsh vegetation growth (Sosnowski et al, 2016). Increased water levels during the dry season might be enough to further sustain additional overall growth of SFG, but perhaps not enough to create overall additional flooding of large areas during an ongoing dry season. However, as previously noted, the variations within the wetland vegetation covers differ spatially, and the large decrease in lake water levels during 2010 showed different vegetation responses within the Ez Zeraf Game Reserve and Shambe National Park. The lower seasonal water levels could cause vegetation blockages within the marshes, as a result of enhanced vegetation growth, thus potentially increasing local lateral flooding (Sosnowski et al, 2016) as seen within Shambe National Park during March 2002.

6.2.2 Influences by Lake Victoria and Lake Kyoga

No statistically significant relationship was found between the vegetation variables and water levels in Lake Victoria or Lake Kyoga. Being the main water basin sustaining the White Nile, Lake Victoria water levels were expected to display some significant associations with the vegetational changes within the Sudd Wetland. However, as Lake Albert is the last water basin before the Nile River reaches the Sudd wetlands, the water level height might give a more accurate representation of the variations in the water amount reaching the wetland. Nonetheless, previous studies have reported large changes in wetland cover and overall wetland area extent to primarily be influenced by the water contribution from Lake Victoria (Mohamed and Savenije, 2014; Sene, 2000). Despite the statistical correlation between the water levels of Lake Victoria and the mean NDVI of the study area displaying no statistical significance, the relationship observed can be considered reasonable, seeing the results of the previous studies observing statistically significance between wetland vegetation cover and Lake Victoria levels during the preceding wet season (Sosnowski et al, 2016). Extending the dry season to include additional months besides March might increase the performance of the statistical analysis. Furthermore, analysing the upper average deviations of water level heights within the water basins, instead of using the overall mean heights, could potentially provide a more accurate representation of waterflow variations.

6.2.3 Influences by average precipitation patterns

The average precipitation within the used precipitations boundaries did not appear to influence the wetland vegetation cover area or mean NDVI, as no statistically significant relationship between the precipitation and the obtained environmental variables was found. The analysis indicates that an overall extrapolation of spatial and temporal precipitation averages does not perform well for assessing potential influence on the wetland vegetation cover. Only the correlation with overall OW cover extent displayed a potential, non-significant, casual association with the precipitation averages, indicating a possible fair agreement of high precipitation averages increasing the OW cover. Significant hydrological influences on the Sudd wetland have previously been observed to primarily be the results of the lake levels, in addition to precipitation (Di Vittorio and Georgakakos, 2018; Mohamed and Savenije, 2014; Sutcliffe and Parks, 1987). The temporal and spatial resolution of the precipitation patterns needs to increase in order to obtain short term influences on the wetland vegetation covers. Additionally, seasonal values of maximum precipitation might, similarly to the lake water levels, provide a more accurate representation of the rainfall runoffs influencing the wetland cover.

6.3 Assessment of armed conflicts

6.3.1 Conflict frequency and mean NDVI

The ongoing conflicts in South Sudan are notoriously complex and deeply rooted. Assessing the potential drivers of the frequency and magnitude of conflicts associated with herder-pastoralists are challenging. Once a longstanding historical feature of many pastoralist societies, the endemic cattle raiding has been considerably exacerbated by the gain of military and political objectives (Wild et al, 2018). Previous studies focusing on South Sudan have showed temperature anomalies to influence the risk of conflicts (Maystadt et al, 2014). Furthermore, the competition of natural resources appears to be potential key divers of conflicts in the regions dominated by pastoral cultures (Maystadt et al, 2014; Tiitmamer et al, 2018). The yearly number of reported conflicts associated with herder-pastoralists during the dry season within 30 km of the protected areas displayed a statistically significant positive correlation with the mean NDVI of the protected areas. The analysis suggests years with an elevated mean NDVI also had an increase in documented conflicts, contradicting previous literature proposing potential drivers of conflicts being scarcity of natural resources such as water and palatable grazing grounds. The ability of the Sudd wetland to endure events of intense droughts through the sustained inflow of the White Nile makes the wetland an area of refuge for both people, livestock, and wildlife. An increase in yearly conflicts in correspondence to a higher NDVI could possibly be the result of the migration of communities to the wetland in search of natural resources when much of the surrounding areas remain resource depleted. However, the Sahel region have reportedly been experiencing an overall trend of greening since the 1982, and the most important factors influencing the vegetation progression includes precipitation and temperature (Yang et al, 2019). Therefore, an increase in conflict incidents in association with higher values of NDVI might be coupled with increasing temperatures, as previous studies have demonstrated a link between conflicts and temperature anomalies (Maystadt et al, 2014).

6.3.2 Distribution of conflicts around the wetland

South Sudan is highly prone to climate variability (Ajak, 2018). Climate induced extremes such as intensified and prolonged events of flooding and droughts causes scarcity of natural resources forcing competition between communities (Tiitmamer et al, 2018). The reported conflicts were mostly located in larger cities and towns (figure 14). However, several conflicts appear to be distributed in close proximity to the ethnic borders between the pastoral groups of Nuer, Dinka and Shilluk. Violent competitions between and among the pastoral groups over limited natural resources have been documented as a result of intense pressure from climate induced stressors (Tiitmamer et al, 2018). In the town of Yirol, at least 75 people were reported killed and thousands more displaced when a non-specific inter-clan violence, incited by cattle rustling and disputes over grazing grounds and water, erupted in April 2005. Coupled Models (CMIP5) have projected an increase of mean annual temperatures by 1°C and mean annual precipitation by 4% in South Sudan by the mid-century (World Bank Climate Change Knowledge Portal, 2021). Prolonged dry periods and erratic rainfalls would result in large losses of livestock, displacement of people, and disruptions of critical ecosystems (Ajak, 2018). Therefore, an increase in climate extremes would exacerbate resource-based conflicts already experienced in the region.

Among the protected areas, Ez Zeraf Game Reserve had the fewest number of reported conflicts during the dry season in addition to having lower variations in wetland cover distribution, similar to the variations observed within the Sudd Ramsar Site. Shambe National Park experienced the most conflicts associated with herder-pastoralists during the dry season 2000-2020, in addition to having large variations in wetland cover extent. Research have shown wildlife population declining with an increase in conflict frequency (Daskin and Pringle, 2018). Furthermore, periodic climate extremes are known to increase the unavailability of important natural resources such as palatable grasslands and water (Tiitmamer et al, 2018; Maystadt et al, 2014), and may further endanger wildlife through increased poaching and habitat loss. Intensified and prolonged events of droughts are central threats for large mammal populations such as the African elephant, giraffe and white eared kob (UNDP, 2007; Dunham, 1994). However, risk-tolerant conservation approaches have been recommended and post-conflicts conservation initiatives in collaboration with humanitarian relief organizations proven successful, resulting in both poverty alleviation and improved conservation measures of protected areas (Daskin and Pringle, 2018).

6.3.3 Further associations with the environmental variables

No statistical significance was found between the yearly number of conflicts and the wetland vegetation cover extent and hydrological variables. Similarly, no statistical relationship was found when analysing the potential influences of the yearly dry season fatalities. Indicating that the severity of the conflicts had no statistically significant relation to the hydrological or vegetational variables, and instead were most likely related to political and military objectives. An increased spatial and temporal resolution of the hydrological variables might however have resulted in a higher likelihood of detecting any significant relationship with the reported conflict frequency and magnitude. Furthermore, assessing the vegetation cover dynamics beyond the borders of the protected areas could potentially provide stronger associations between the conflicts and vegetation covers. However, the intentionally broad wetland vegetation cover classes might not be suitable for assessing potential influences on conflict frequency and magnitude. More narrower categories of the most prominent utilized natural resources by pastoral cultures, such as water and palatable grasslands, might show stronger associations, as limitations of these natural resources have been previously observed as key divers of conflicts in the regions dominated by pastoral cultures (Maystadt et al, 2014; Tiitmamer et al, 2018).

6.4 Data uncertainties

During the earlier years of the study period, the water basins had fewer documented measurements of lake level heights. During some of the months, lake level data was even non-existent, meaning that seasonal averages were based upon just a few measurements. Furthermore, the satellite retrieved precipitation product (GPM) have previously been observed to overestimate overall precipitation patters when used in arid regions (Lu et al, 2018), however, the GMP have seen to perform well during extreme precipitation events (Liu et al, 2020). Additionally, the GMP measurements began acquiring data in June 2000, resulting in the precipitation average during 2000 not including the months of April and May. The obtained conflict dataset is furthermore prone to uncertainties due to its potential of incorrect conflict encoding. Moreover, conflicts in rural locations are more difficult to obtain a high accuracy of geographic precision (Eck, 2012). These uncertainties should be noted and may have had an affect the obtained results.

6.5 Further analysis

In a region highly subjected to climate extremes, the ability of the Sudd wetland to withstand intense national events of droughts through a sustained inflow of the White Nile highlights the ecological and socio-economic importance of the wetland. The hydrological regime of Lake Albert is observed to influence the vegetation cover extent of SFG and M cover within the Sudd wetland. Furthermore, previous studies have also found Lake Victoria to highly influence the vegetation cover extent of the Sudd wetland. Therefore, major environmental risks would include the construction of large hydroelectric power dams of the main water basins or the continuation of the Jonglei Canal (Ministry of Environment, 2015). Additional assessments including air temperature variations could further indicate potential influences of climatic extremes on the Sudd wetland NDVI and vegetation cover extent. Moreover, analysing temperature variations would also contribute to the understanding of possible linking between climate variations and conflict incidents. Further analysis could have analysed local changes within the wetland and their potential hydrological divers, as the spatial variation in wetland vegetation cover indicated significant differences between the protected areas. An increase in spatial resolution for wetland vegetation monitoring could improve the detail of potential local measurements. However, the issue of missing ground control data for accuracy assessment remains.

7. Conclusion

The hydrological regime has previously been observed to influence the Sudd wetland, and furthermore upholding the large ecological and socio-economic values of the wetland habitats. This thesis study found the variations of Lake Albert water level significantly influencing spatial and temporal variations in the vegetation cover extent of the SFG and M classes, corresponding with the results of previous studies. The continuously high inflow of water from the water basin appeared to possibly have sustain a high NDVI within the wetland during years of nationwide droughts. However, the water levels of Lake Victoria and Lake Kyoga as well as the average precipitation showed no statistical association with the mean NDVI and wetland vegetation cover extent. The endemic cattle raiding has been considerably exacerbated by the gain of military and political objectives. Furthermore, the competition of natural resources has previously been reported as a potential key driver of conflicts in regions of pastoral cultures. This study found the yearly number of reported conflicts associated with herder-pastoralists to be associated with an elevated wetland NDVI. Being mostly reported within larger cities and towns, the conflicts were also distributed near ethnic boarders of indigenous pastoral cultures. Moreover, the magnitude of conflicts was not found to be significantly influenced by vegetation or hydrological variables. The wetland cover classification further highlighted spatial variations in NDVI and vegetation cover between the protected areas. Monitoring changes within these areas help us better understand how the wetland is affected by different mechanisms and processes over time, and further contributes to the protection of the wetland. In a region predicted to experience continued political instability and an increase of climatic extremes, the wetland and its ecosystems are of high importance for the surrounding wildlife and pastoral communities. The usage of satellite remote sensing for monitoring the variations in wetland vegetation cover have shown to be an effective method for observing large remote areas otherwise restricted by inaccessibility and regional instabilities.

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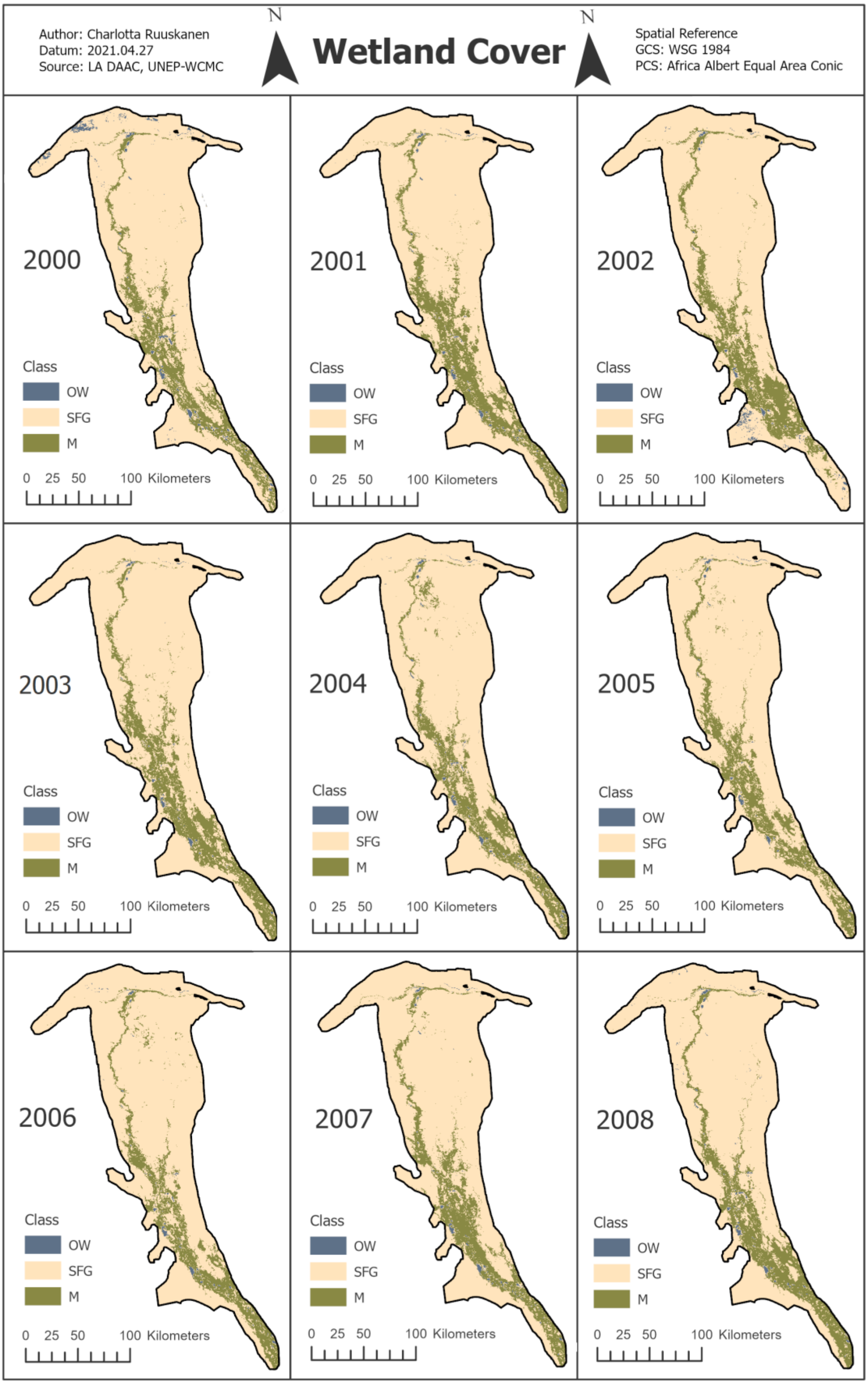
Appendix

Table A1: The yearly derived statistical thresholds for the wetland cover classes; open water, seasonally-flooded grassland, and marsh. Similarly to the article by Sosnowski et al (2016), any pixels containing and NDVI value below two standard deviations under the calculated mean was categorized as open water. Likewise, pixels with NDVI values above one standard deviation over the calculated mean was categorized as marsh. Pixel values between the classes of open water and marshland was categorized as seasonally flooded grassland.

Year	**Open water**	**Seasonally-flooded grassland (mean)**	**Marsh**
2000	0.17	0.35	0.53
2001	0.12	0.33	0.54
2002	0.14	0.33	0.52
2003	0.08	0.30	0.52
2004	0.14	0.34	0.54
2005	0.13	0.33	0.53
2006	0.14	0.33	0.52
2007	0.14	0.32	0.51
2008	0.17	0.36	0.54
2009	0.13	0.34	0.55
2010	0.06	0.27	0.49
2011	0.08	0.31	0.55
2012	0.07	0.29	0.51
2013	0.16	0.38	0.60
2014	0.20	0.40	0.59
2015	0.23	0.39	0.56
2016	0.15	0.36	0.56
2017	0.17	0.35	0.53
2018	0.17	0.37	0.57
2019	0.11	0.33	0.55
2020	0.18	0.38	0.58
Mean	0.14	0.34	0.54


Author: Charlotta Ruuskanen
Datum: 2021.04.27
Source: LA DAAC, UNEP-WCMC
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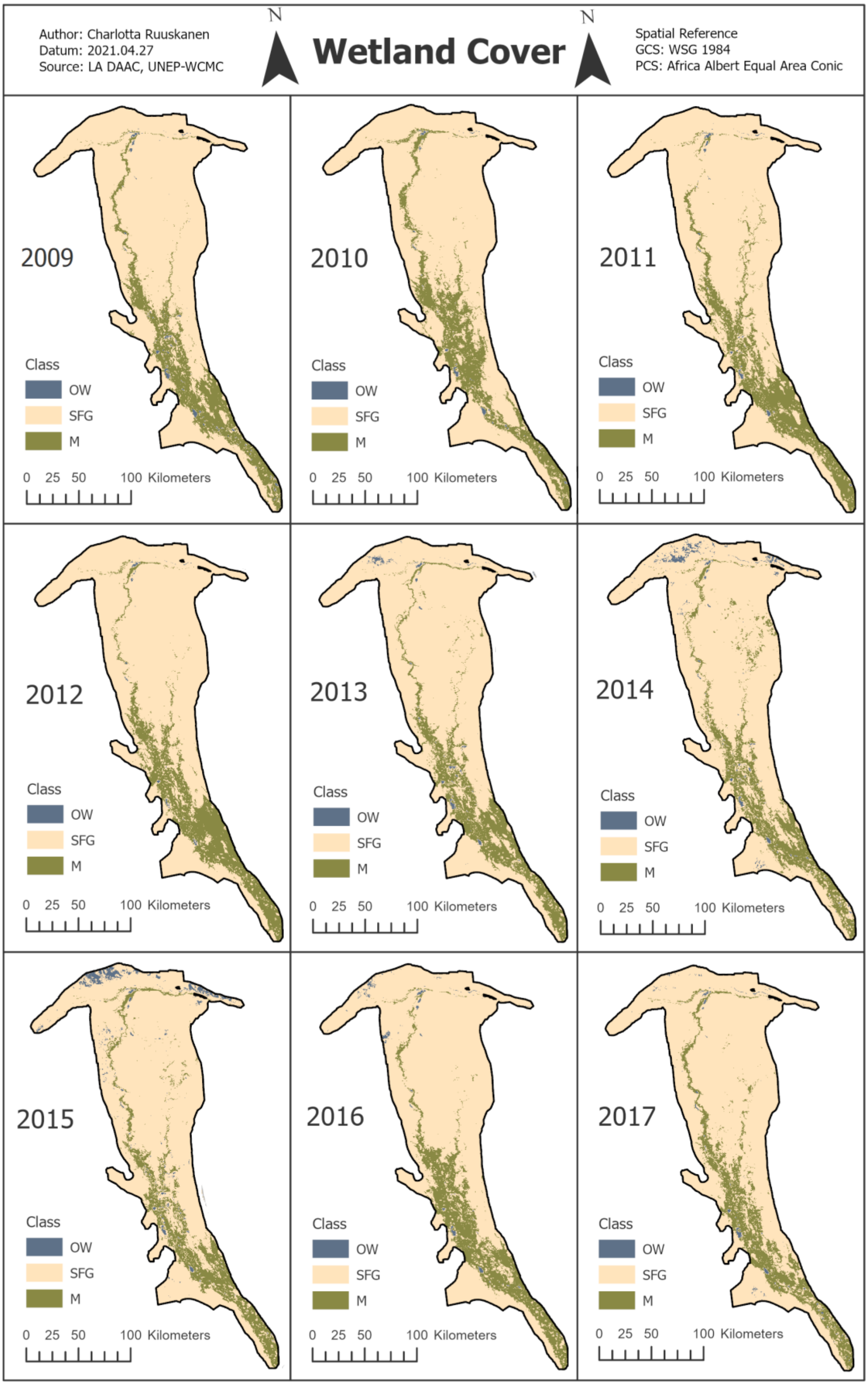
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Datum: 2021.04.27
Source: LA DAAC, UNEP-WCMC
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0 25 50 100 Kilometers

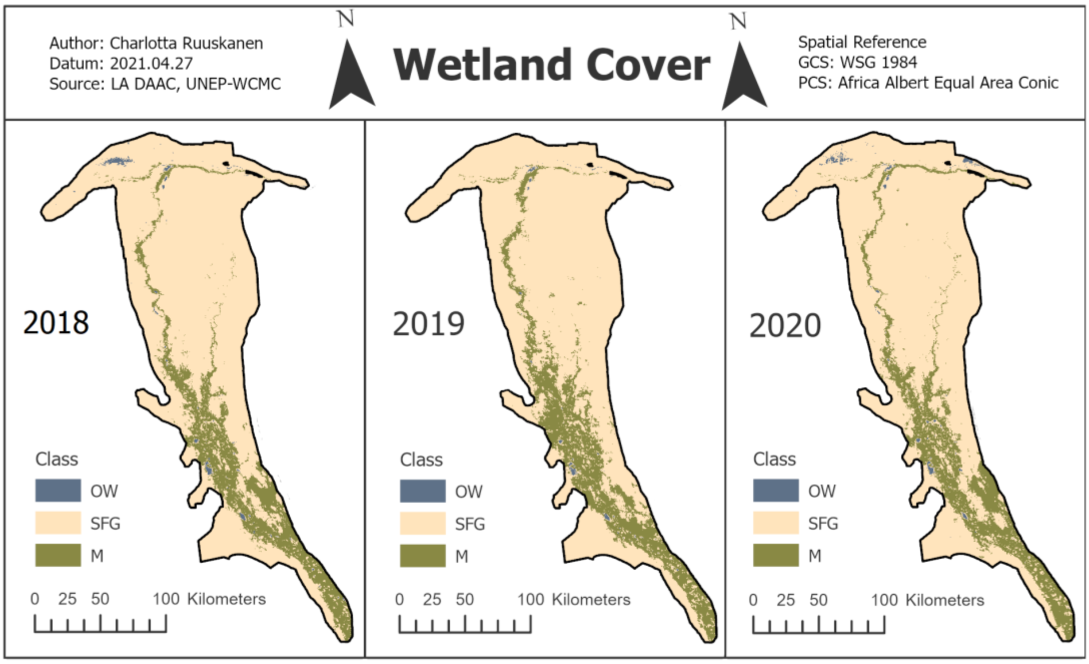

Figure A2: The wetland cover classes; open water (OW), seasonally-flooded grassland (SFG) and marsh (M), within the study area in March 2000-2020.