Characterization of plant-water interaction in Kilombero River Catchment in Tanzania using Normalized Difference Vegetation Index (NDVI)

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Preface

This Master’s thesis is Michael Getachew Minas’ degree project in Physical Geography and Quaternary Geology at the Department of Physical Geography and Quaternary Geology, Stockholm University. The Master’s thesis comprises 45 credits (one and a half term of full-time studies).

Supervisors have been Steve Lyon and Ian Brown at the Department of Physical Geography and Quaternary Geology, Stockholm University. Examiner has been Jerker Jarsjö at the Department of Physical Geography and Quaternary Geology, Stockholm University.

The author is responsible for the contents of this thesis.

Stockholm, 6 November 2014

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Abstract
Remote-sensing based indices such as Normalized Difference Vegetation Index have yielded valuable information about plant health. As the availability of water is one of the factors that controls plant's response to their environment, it is possible to indirectly study the hydrology of an area via vegetation indices. Hence the thesis work used this tool to characterize the potential shifts in vegetation cover within and between years in Kilombero river catchment in Tanzania and make connection to the hydrology in the area. Separate time series analyses conducted on data pertaining to NDVI values and the areal coverage variability of arbitrarily defined NDVI-classes. The former data was extracted from a naturally vegetated wetland in the middle of the catchment while the latter from the topographically defined areas of the catchment. Results from the analyses showed that both datasets are sensitive to the seasonal rainfall while at inter-annual scale the areal coverage variability displayed significant correlations with past precipitation. Meanwhile the relatively higher sensitivity of the lowland area’s NDVI to precipitation conforms to the initial assumption which emphasizes the importance of the wetland sub-catchment code-named 1KB17 in describing Kilombero’s hydrology. But the datasets show weak trends and it was not possible to make accurate future predictions on the hydrological conditions in the area. Meteorological distortions like clouds and environmental processes such as climate patterns or disturbances might have caused the problem in trend detection. Further studies needed to shed more light on the connection between land cover and hydrologic response in Kilombero.

Key words: NDVI, NDVI classes, areal coverage, time-series analyses, hydrological data
CHARACTERIZATION OF PLANT-WATER INTERACTION IN KIOMBERO RIVER CATCHMENT IN TANZANIA USING NORMALIZED DIFFERENCE VEGETATION INDEX (NDVI)
Acknowledgements

I would like to start by extending my gratitude to the thesis advisors Steve Lyon and Ian Brown. The consultations and feedbacks have been invaluable not only to the success of this thesis work but also in helping me attain vital knowledge in the subject area. Thank also goes to PhD students Rene P. Mbanguka and Alexander Koutsouris for sharing information on the physical environment of the study area and for providing the much needed hydrological data. Further I would like to appreciate Maria Damberg for her support during my studies at Stockholm University.

The solid support and encouragement I got from families and friends kept me motivated throughout the thesis work and I appreciate it much.

Last but not least I would like to thank Stockholm University and the Swedish government for making this high quality Masters Level study available for free.
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1. Introduction

1.1. Background and research goals
In order to grow, survive and reproduce plants are highly dependent on their physical environment. To capture and understand plant response to their environment, it is necessary to use quantification tools. Remote-sensing is one such tool since the nature of the reflected light, via its intensity, spectral properties, and spatial or angular properties, gives information about the surface being studied (Jones and Vaughan, 2010).

Many studies have made use of remote-sensing to comprehend the dynamics of both natural vegetation covers and agricultural lands. It has been applied in irrigated land and forest management (Ha et. al., 2012; Prabakaran et al., 2013) as well as in issues of land-cover changes such as deforestation, cropland decrease, forest degradation and desertification (Lepers et al. 2005). In addition, it has applicability in hydrology as it is used in deriving the constituent variables in water balance equation (Gao et. al., 2009; Gokmen et. al., 2013) and in lake water volume calculations (Lu et. al., 2013).

Remote-sensing tools are also used for the purpose of evaluating plant-water interaction and for describing the hydrological condition in the areas studied. It is assumed that plants constitute an important intermediate link in the earth’s pedosphere, atmosphere and hydrosphere. Hence, understanding the close link that exists between plant health and the climate is important (Zhong et al., 2010). To this end, indices derived from remote-sensing data are utilized as proxy for the land surface response to identify drought signatures and wetter conditions (Anyamba and Tucker, 2005; Muthumanickam et al., 2010; Dutta et al., 2012); in evaluating the impact of agricultural land use change on water resources (Elhag et al., 2013) and in evaluating climatic anomalies related to ENSO events using the spatial patterns of NDVI variations (Erasmi et al., 2009; Liu and Juarez, 2000; Anyamba et al. 2000). Meanwhile, other researchers used such index-based tools in soil and water balance modeling, which have helped efforts to estimate evapotranspiration (Campos et al., 2013; Senay et al., 2011).
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Evidently in any hydrological studies data of adequate quality and appropriate length of records are necessary (Raghunath, 2006). In this regard remote-sensing has important applicability, especially in regions with limited water resources and poor hydro-climatic data like Africa. The current climate data infrastructure in Africa is not only unreliable, but also built upon low quantity of meteorological stations. Too often the collected data have not been digitized (UNDP, 2011). There is also constraint in accessing even the existing data because it is not reported internationally by African countries (Washington et al., 2004).

Tanzania is one of the African countries where lack of in situ data posed problems in water resource management studies (Deus, 2013; Scheibler, 2012). Reliable output from such studies would be valuable as the increasing population in many rural areas of the country is contributing to changes in land use and cover patterns as well as land fragmentation and livelihood insecurity (Kangalawe and Lyimo, 2010). Furthermore the current agricultural practices lack modernity and food product is still dependent on seasonal rainfall (ERB, 2006; Valimba et al., 2006). Nevertheless the country has about 0.9 million hectares irrigable lands, but only 15% of it is currently irrigated (FAO, 2002). Therefore, developing dry land irrigation agriculture to extend growing seasons has potential to increase agricultural production and reduce poverty (ERB, 2006; Lyon, 2011).

To these ends, this thesis work aims to use remote sensing tools to characterize the potential shifts in vegetation cover within and between years in Kilombero River Catchment in Tanzania and see if there is a connection to the hydrology in the area. It is hypothesized that any seasonal variability or potential inter-annual trends in the extent of wetland area in the Kilombero Valley would impact the area’s hydrological response. This can be indirectly assessed by determining the land cover’s reflective properties using the Normalized Difference Vegetation Index (NDVI) within a given time frame of interest and comparing variations with available hydrological data.
1.2. Remote-sensing tools

1.2.1. Radiative properties of vegetation, soils and water

The chemical and structural characteristics of leafs control how plants interact with incoming radiation. Leaf age, leaf thickness, leaf structure and leaf water content are important in this respect. The recorded spectral signature of plants can help infer plant growth and development, as well as specific stresses, which can change the structural and chemical characteristics of the plants. In stark contrast to vegetation where a sharp increase in reflectance is generally observed around 700 nm, soils on average tend to show a rather smooth increase in reflectance from the visible to the near infrared. As opposed to soils and vegetation, pure water tends to reflect a much smaller proportion of incident radiation and is almost completely transparent to shorter wavelengths of visible radiation with significant absorption only at wavelengths greater than 1100nm. In the visible, near and mid-infrared regions reflectance remains less than about 3%. (Jones and Vaughan, 2010)

1.2.2. Vegetation Indices

There are several vegetation indices that are derived from radiometric data. These indices provide means to assess the amount of green vegetation or bio-mass present in an area. As discussed in the previous section high reflectance from vegetation occurs at around 700 nm. This unique spectral property lays the basis for the existing indices of vegetation. The most common approaches in which the red and near infrared vegetation responses are combined to derive quantitative indices include Normalized difference vegetation index (NDVI), Difference vegetation index (DVI) and Ratio vegetation index (RVI).

The Normalized Difference Vegetation Index (NDVI) is the most widely used of all available indices and forms the basis for the others. Both reflectance and radiances can be applied in the calculation of NDVI. Similar to the equation (1) below radiances received at the detector (DNs) are often used in place of reflectance, which is advantageous since the latter improves the correction for differences in incident radiation and for absorption and scattering in the atmosphere.

\[ NDVI = \frac{p_{NIR} - p_{R}}{p_{NIR} + p_{R}} \]
Where, pNIR and pR represents reflectance in the near-infrared and red spectra, respectively. One should notice that the sum (pNIR + pR) results in twice the average reflectance in the wave length range between near-infrared and red. Division by this factor reduces the effect of non-uniform illumination related to aspect, and thus helps to make for better comparability of the vegetative index (VI) across an image. Furthermore it generally scales between 0 and 1 except in the presence of cloud, snow and water surfaces where negative values emerge. Studies (e.g., Jones and Vaughan, 2010; Tucker et al., 2005) point out that NDVI values for vegetated land is between 0.10 and 0.70, where densely vegetated areas have NDVI values greater than 0.50.

Various authors have attempted to map land-cover phenology, land-cover dynamics and land degradation through the analysis of multi-temporal NDVI data (Bie et al., 2010; Cayrol et al., 2000; Ledwith, 2000; Eerens et al., 2001; Brand and Malthus, 2004; Budde et al., 2004; Fraser et al., 2009; Julien and Sobrino, 2009). Its use in monitoring vegetation in arid and semi-arid areas (Tucker et al., 1985; Anyamba and Tucker, 2005) is attractive. The comprehensive NDVI images derived from the Advanced Very High Resolution Radiometer of the National Oceanic and Atmospheric Administration (NOAA-AVHRR) provide opportunities for time-series analyses of changes in land use and cover on a global scale (Fuller, 1998).

The main drawback with NDVI is related to factors such as seasonal and diurnal variation in atmospheric water vapor and atmospheric aerosol content which can cause significant variations in NDVI not related to actual vegetation cover. The reflective nature of bare soil in arid and semiarid areas can also affect NDVI (Anyamba and Tucker, 2005). The ‘de-clouding’ approach presented by de Bie et al. (2010) can partly reduce the effects the mentioned factors have on NDVI. In this approach, only those pixels that satisfy certain quality requirements are retained. These requirements are (i) a ‘good’ radiometric quality for the red and near infrared and (ii) the pixels are not labeled as ‘shadow’, ‘cloud’ or ‘uncertain’ but as ‘clear’ in the quality flags by pixels accompanying the NDVI data. The removed pixels will subsequently be labeled as ‘missing’. Yet another approach by de Bie
et al. (2013) offers a method of masking by area (class) the periods when pre-cleaned NDVI values remain affected by clouds. It requires no additional data for execution purpose but involves unsupervised classification of the imagery to carry out the evaluation of class-specific mean NDVI and standard deviation values over the time.

1.3. **The study area**

1.3.1. *General basin description*

The study area, Kilombero River Basin, is located in the Southern part of Tanzania and forms one of the four principal sub-basins of the Rufiji River Basin. It has an area of approximately 39,990 km² (ERB, 2006). The basin of the Kilombero River is oriented from SW to NE and situated between Longitudes 34°33’E and 37°20’E and between Latitudes 7°39’S and 10°01’S (Figure 1). Steep slopes rising up to 2576 m ASL bound the Northwestern side of the catchment meanwhile along the southeastern side the land raises more gradually, eventually changing to a steep escarpment which reaches a maximum height of 1516 m ASL (Hughes and Hughes, 1992; RIS, 2002). The basin is divided into six sub-catchments namely 1kb4, 1kb8, 1kb10, 1kb14, 1kb17 and 1kb15a (Yawson, 2009). At its outlet Kilombero basin’s outflow is 542,2 m³/s as measured at the gauging station code-named 1kb17. This station is located at the most downstream part of the valley and considers drainage that represents the whole basin (Scheibler, 2012).

The main feature of the valley is the Kilombero Floodplain also known as Kibasila swamp. This floodplain holds a mixture of swamps, lakes, rivers, riverine forest and grassland and further out to the edges it is dominated by the Miombo woodland. The annual flooding raises the water levels between November and April with most of the peak flows occurring in March to April. These fluctuations are vital for wildlife migration, fish production and soil fertility (RIS, 2002).

The Kilombero River Basin has semi-arid climate and it is one of the most productive agricultural areas in Tanzania. Approximately 329,600 hectares are irrigable. The main crops in the area are rice, maize, bananas and sugarcane. In the bigger Rufiji River Basin
approximately 3 million people live and in the Kilombero Valley Ifakara is the main city. There are many small villages distributed throughout the catchment (ERB, 2006).

Figure 1. The study area.

1.3.2. Climate
The Kilombero Basin is situated in tropical humid zone and in general has a semi-arid climate. In this river basin topography has control over the local climate. The mountainous regions are cooler and wetter, with a mean daily temperature of 17°C average annual precipitation totals ranging from 1,500 to 2,100 mm meanwhile the lowlands are hot and humid with a mean daily temperature of 24°C and annual precipitation between 1,200 and 1,400 mm (ERB, 2006). The rainy season in both the mountainous and the low land areas is unimodal. It occurs between mid-November and mid-May accounting for 80 to 90% of the yearly precipitations (RIS, 2002). In the remaining portion of the year the basin receives
little precipitation except at some localities on the mountainous area (ERB, 2006; IRA, n.d.).

1.3.3. Soil and vegetation

The main soil type in the flood plain is the black cotton soil locally with lighter sandy soils where the former have capacity to retain water for a relatively long period of time. In most areas the soil moisture remains near saturation level up to 3-6 months after the rainy season (RIS, 2002), but in other parts the soil drains immediately after the end of the rainy season (Kangalawe & Liwega, 2005). Meanwhile on the gentle slopes and broad hilltops distinctly red, deep, freely drained, stone-free weakly acid clays, with moderate levels of soil fertility are found (Chase, 1992).

There is a distinct graduation in the major vegetation types from the river channels to the mountains. The seasonally inundated valley bottoms are characterized by swamp grassland and small patchy areas of flood resistant woodlands. It is bounded by the transition areas to the highlands containing wooded grasslands which gradually transform into an extensive Miombo belt. This belt is an open woodland habitat although trees do interconnect in many areas. Due to fire in the wooded short grass in the open woodland, there is often a distinct boundary between trees and short grass. (Chase, 1993; RIS, 2002). At higher altitudes of the mountain ranges to the North and South of the valley evergreen forests are the dominating vegetation types (Kangalawe and Liwenga, 2005).

2. Data base

2.1. Introduction

This study makes use of NDVI and digital elevation model (DEM) data from the study area as well as ArcGIS shape files representing hydrology, land cover, soil, geology and landforms. These are discussed in the following sections.
2.2. **Normalized Difference Vegetation Index (NDVI)**

The NDVI maps are the main inputs for this study and can be readily obtained from sensors such as Advanced Very High Resolution Radiometer (AVHRR) and Moderate-Resolution Imaging Spectrometer (MODIS). Both sensors are capable of detecting the red and near infrared bands. For this study the MODIS data set was chosen as it has a higher spatial resolution in the visible red and near infrared bands and has one of the most accurate calibration sub-systems ever flown on a remote-sensing instrument. It also has a higher radiometric resolution than AVHRR (Jones & Vaughan, 2010).

MODIS (or Moderate Resolution Imaging Spectro-radiometer) is a newer generation instrument onboard the Terra satellite launched December 18, 1999 and the Aqua satellite launched May 4, 2002 (Beck et al., 2011). Terra's orbit around the Earth is timed so that it passes from north to south across the equator in the morning, while Aqua passes south to north over the equator in the afternoon. Terra MODIS and Aqua MODIS are viewing the entire Earth's surface every 1 to 2 days, acquiring data in 36 spectral bands, or groups of wavelengths. These data will improve understanding of global dynamics and processes occurring on the land, in the oceans, and in the lower atmosphere.

For this project, 12 years MODIS-NDVI data, namely Global MOD13Q1, with a temporal acquisition frequency of 16 days was downloaded from the NASA website. The data sets are provided in 250-meter spatial resolution as a guarded level-3 product in the Sinusoidal projection. Furthermore, this Global MOD13Q1 dataset contains both NDVI and EVI products which are computed from atmospherically corrected bi-directional surface reflectance that have been masked for water, clouds, heavy aerosols, and cloud shadows (USGS, 2014).

The precipitation in the study area has uni-modal distribution. Hence to capture shifts in vegetation cover, which are directly depends on to the length of the rainy season, special focus was given on the part of the year representing seasonal transitions. Therefore datasets between March and October were downloaded in order to capture the shift at the end of
May. Furthermore to reduce the size of input data for the analyses only one 16-days image were downloaded for each of the relatively drier months (September and October). Hence for this study 12 years x 6 months x 2 16-days image (wetter months) and 12 years x 2 months x 1 16-days image (drier months) gave a total of 168 images.

2.3. DEM (digital elevation model)
The DEM is used in reclassifying the study area into lowland and highland classes. Analyses on the selected NDVI classes’ areal coverage variation in these two topographic classes were done. The study area’s DEM was extracted from The Shuttle Radar Topography Mission’s (SRTM) digital elevation dataset. SRTM is a product from the National Geospatial-Intelligence Agency (NGA) and the National Aeronautics and Space Administration (NASA). The data were collected in February 2000 on an 11 day mission aboard the Space Shuttle Endeavor using a specially modified radar system. The DEM was aggregated to a 1km spatial resolution (Farr et al., 2007).

2.4. ArcGIS shape files
The shape files were provided by the Kilombero river basin water resources assessment research group at Stockholm University. These files mainly contained data on the study area’s soil types, geology, river network, land form, land cover and watershed.

2.5. Hydrological data
As mentioned in the introductory part of the report, the study area was divided into several sub-catchments, namely 1kb4, 1kb8, 1kb10, 1kb14, 1kb17 and 1kb15a (Yawson, 2009). There is a clear lack of hydro-climatic data from the area. As such only sub-catchments 1KB8B and 1KB18A (Table 2) have hydrological data that overlap in time with the remotely-sensed data. In addition, there is a certain level of uncertainly attached even to the available data as noted in appendix 1. For the purpose of inter-annual comparison the precipitation-to-runoff ratio was calculated and included in the table 1 (See appendix 1). The average precipitation for the whole of Kilombero valley also presented in the table.
3. Methodology

In this study time series analyses conducted on the NDVI data in order to quantify changing trends in ecosystem productivity and its relation to hydrology. Forkel et al. (2013) states that estimation of trends from NDVI time series differs substantially depending on analyzed satellite dataset, the corresponding spatiotemporal resolution, and the applied statistical method. Previous authors were able to produce valuable results via time-series analysis by taking into account the effect of these factors. For example Prabakaran et al. (2013) used time-series analysis in studying phenology of forests to understand the responses of plants towards changes in climatic condition. Tian et al. (2013) used a similar approach in evaluating vegetation change due to coal mining activities. Hill and Donald (2002) used it in estimating spatio-temporal patterns of agricultural productivity in fragmented landscapes.

Keeping a uniform spatiotemporal resolution in the data and employing similar statistical methods, the current study analyzed two time series in order to derive NDVI related trends. The first time series analysis was conducted on the areal coverage variation of selected NDVI classes in chosen areas of interest in the Kilombero river basin. These areas include the lowland, the highlands and the sub-catchment 1KB8B. Meanwhile, in the second mean NDVI values for ‘naturally vegetated’ land-cover class at the middle of the Kilombero river valley were compared across the data available years.

The main software programs used in this study are ArcGIS Version 10 and Microsoft Excel. ArcGIS is the industry standard in GIS and it is a comprehensive system that allows a user to collect, organize, manage, analyze, communicate, and distribute geographic information (ArcGIS, 2014). It goes the same for Excel which has many database analysis functionalities and the files can easily be shared with other Microsoft products. These software programs are provided in the Physical Geography Department’s computer labs and hence chosen for this study. The steps followed in the analyses are discussed below.
Firstly the raw NDVI images were projected into Africa Albers Equal Area Conic projection system. Since the NDVI layer in the Global MOD13Q1 dataset is in 16-bit signed integer format (integer numbers between -32768 to 32767), the next step focused on changing the data into floating numbers with the use of raster calculator. In order to obtain well behaved data ranging between values of 0 and 1 (Jones and Vaughan, 2010), it is necessary to do further processing on the images that were changed into floating point format. Hence all NDVI images were divided by 10000 in raster calculator as per the instructions given on NASA website, before being re-classified into 5 classes (see table 1). The class range is chosen arbitrary as done by previous studies (de Bie et al., 2010; Ali et al., 2013). Further studies (e.g., Jones and Vaughan, 2010; Tucker et al., 2005) point out that NDVI values for vegetated land is between 0.10 and 0.70, where densely vegetated areas have NDVI values greater than 0.50. Hence it assumed that these NDVI classes can be correlated to the land cover types and their associated greenness.

**Table 1. NDVI classes.**

<table>
<thead>
<tr>
<th>NDVI range</th>
<th>Class name/greenness</th>
</tr>
</thead>
<tbody>
<tr>
<td>less than 0.2</td>
<td>Very Low</td>
</tr>
<tr>
<td>0.2-0.4</td>
<td>Low</td>
</tr>
<tr>
<td>0.4-0.6</td>
<td>Medium</td>
</tr>
<tr>
<td>0.6-0.8</td>
<td>High</td>
</tr>
<tr>
<td>0.8-1.0</td>
<td>Very High</td>
</tr>
</tbody>
</table>

Once the NDVI classes were created, the ‘tabulate area’ functionality in ArcGIS was used to extract the areal coverage of each of the NDVI classes that are defined in table 1. Although table 1 has five NDVI classes, focus was given to the medium and high NDVI-classes since the observed areal coverage change patterns in figure 4 can be reasonably represented with the two classes in the areas of interest (lowland, highland and 1KB8). It should be noted that the seasonal areal coverage variability patterns of the adjacent low and very high NDVI-classes have shown similarity with the medium and high-NDVI classes respectively (See figure 4).
It is hypothesized that separate analysis based on topography can aid in understanding the catchment’s hydrology. This is due to the expected sensitivity of the low-land’s vegetation areal coverage to the quantity of water drained from the whole catchment into the wetlands. Hence separate extractions were made for the lowland, the highland and the sub-catchment 1KB8 (hydrology data available). The former two are the results of a supervised classification where a histogram showing pixel counts versus pre-determined elevation ranges were used in selecting the boundary for the two landform classes. In this case a value 456 m chosen as a class boundary between lowland and relatively steep areas. This is based on the presence of relatively large areas in the single elevation class below 456 m (lowlands) and the significantly lesser areal extent of higher elevation classes (valley slopes/ highlands) (See figure 2). Meanwhile the sub-catchment 1KB8 has runoff data and might provide means for direct comparison of the hydrology and the vegetation’s response to water availability. The areal coverage variation patterns in 1KB8 are expected to be similar to the highland landform’s as the sub-catchment is part of the highland land form class.

Several statistical parameters were also extracted for the NDVI values of the different land cover classes in the study area using the ‘zonal statistics’ functionality in ArcGIS. It was discussed in the introduction that sub-catchment 1KB17, which shows spatial overlap with the ‘naturally vegetated wetland’ land cover class, can represent the whole basin from the hydrological point of view (See figure 5). Hence the statistical analysis focused on the mentioned land cover class as it can aid in understanding the sub-catchment’s hydrological response.

The extracted NDVI classes’ areal coverage and the naturally vegetated land cover’s NDVI data underwent further analyses in Excel. Two 16-days NDVI images are averaged to a monthly data both for the NDVI classes and the Naturally vegetated wetland areas. Further analysis conducted on the areal coverage data where they are converted into percentages enabling inter-annual comparison to be made via graph plotting. The two datasets were plotted separately and seasonal/inter-annual trends and patterns derived from the plots.
Figure 2. Flow chart showing the steps taken in the analysis of the data in ArcGIS.
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Furthermore, analyses on the selected NDVI classes’ areal coverage variation for the rainy (March-April-May) as well as for two assumed growing (June-July-August/August-September-October) seasons were conducted. The latter analyses were considered in order to account for the possible lag between precipitation and vegetation/NDVI (Zhong et al., 2010; Kabthimer, 2012).

4. Results

The results from the study are presented primarily in the form of maps, tables and graphs. They are grouped into two parts, where in the first output from the analysis on the NDVI values for the naturally vegetated wetland land cover class shown. Meanwhile in the second the areal coverage variations of the selected NDVI classes in the lowland, high-land and sub-catchment 1KB8 presented.
4.1. **NDVI in the naturally vegetated wetland**

As per the discussion in the methodology section, analysis on the seasonal and inter-annual variation of the NDVI value for ‘naturally vegetated wetland’ land cover class located in the middle of valley area performed (See figure 5). The figure shows that the whole naturally vegetated wetland area fall under the important sub-catchment 1KB17.

The graph plots for the naturally vegetated wetland (NVW) are presented with figures 6 and 7. Figure 6 shows the seasonal variation in the NDVI values for the years 2001 to 2012. The corresponding standard deviation calculated and presented on a table accompanying the plot in figure 6. While figure 7(a) and 7(b) represents respectively the variation in the yearly mean NDVI values and precipitation between 2001 and 2010. The appended table shows the Pearson correlation coefficients between the mean NDVI values and precipitation in the naturally vegetated area in the time periods 2001-2010 and 2004-2010.

![Figure 5. The naturally vegetated wetland (NVW) area.](image-url)
CHARACTERIZATION OF PLANT-WATER INTERACTION IN KILOMBERO RIVER CATCHMENT IN TANZANIA USING NORMALIZED DIFFERENCE VEGETATION INDEX (NDVI)

The mean NDVI values in the naturally vegetated area between the years 2001 and 2010 presented in figure 7(b) while whole catchment's precipitation with figure 7(a). The two are compared using Pearson’s correlation coefficient (r). Visual similarities were observed in the graph plots (see figure 7(a) and 7(b)) between the years 2004 and 2010. Hence two coefficients were calculated and presented in the attached table, where the first covers all the years while the other the specified range respectively.

<table>
<thead>
<tr>
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Pearson’s coefficient (r)  
2001-2010 0.2788  
2004-2010 0.7208

4.2. Inter-annual areal coverage variations in areas of interest

The selected NDVI classes’ mean areal coverage values in the rainy (March-April-May) as well as in the two assumed growing (June-July-August/August-September-October) seasons were processed in excel and the results presented in figures 8-10 for each of areas
of interest. Trend line accompanied each plots and the corresponding R-square values are also shown.

Figure 8. High (dark green curve) and medium (light green curve) NDVI classes’ areal coverage variations in the rainy season (a) as well as in the plant growth periods (lag-1 (b) and lag-2 (c)) in the lowland area between the years 2001 & 2012.

Figure 9. High (dark green curve) and medium (light green curve) NDVI classes’ areal coverage variations in the rainy season (a) as well as in the plant growth periods (lag 1 (b) and lag 2 (c)) in highland area between the years 2001 & 2012.
CHARACTERIZATION OF PLANT-WATER INTERACTION IN KILOMBERO RIVER CATCHMENT IN TANZANIA USING NORMALIZED DIFFERENCE VEGETATION INDEX (NDVI)

4.3. Seasonal areal coverage variations in the areas of interest

The class ranges in table 1 form the basis to reclassify the NDVI images in the study area as shown on the figures in appendices 2-13 (with representative images of the dry and wet seasons). The extracted data for each of areas of interest were processed in excel and the plots are presented also in appendices 2-13. These plots show the areal coverage variation for the two NDVI classes, namely medium (light green) and high (dark green).

Each year’s areal coverage plots of the selected NDVI classes are shown super-imposed in figures 11(a)/11(b), 12(a)/12(b) and 13(a)/13(b) for the lowland, high-land and 1KB8 respectively. These figures show the general trend the data followed between the years 2001 and 2012. The mean areal coverage values for the selected NDVI classes through the years are also presented in the same figures (See figures 11(c), 12(c) & 13(c)). For each mean value plots a corresponding standard deviation table presented. Meanwhile the range...
in areal coverage values and the correlation coefficients between the areas of interest for the selected NDVI-classes presented in tables 2 and 3 respectively.

![Seasonal areal coverage variations of the high-NDVI class (a), the medium-NDVI class (b) and mean value curves of the two classes (c) for years 2001 to 2012 in the sub-catchment 1KB-8. The high NDVI class is represented with the dark green curve & the medium NDVI class with the light green curve. The appended table shows the standard deviations for the monthly mean NDVI values calculated across the years.](image)

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Figure 11. Seasonal areal coverage variations of the high-NDVI class (a), the medium-NDVI class (b) and mean value curves of the two classes (c) for years 2001 to 2012 in the sub-catchment 1KB-8. The high NDVI class is represented with the dark green curve & the medium NDVI class with the light green curve. The appended table shows the standard deviations for the monthly mean NDVI values calculated across the years.
CHARACTERIZATION OF PLANT-WATER INTERACTION IN KILOMBERO RIVER CATCHMENT IN TANZANIA USING NORMALIZED DIFFERENCE VEGETATION INDEX (NDVI)

Figure 12. Seasonal areal coverage variations of the high-NDVI class (a), the medium-NDVI class (b) and mean value curves of the two classes (c) for years 2001 to 2012 in the highland area. Note that the high NDVI class is represented with the dark green curve & the medium NDVI class with the light green curve. The appended table shows the standard deviations for the monthly mean NDVI values calculated across the years.

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<th>July</th>
<th>August</th>
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<tbody>
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Figure 13. Seasonal areal coverage variations of the high-NDVI class (a), the medium-NDVI class (b) and mean value curves of the two classes (c) for years 2001 to 2012 in the lowland area. Note that the high NDVI class is represented with the dark green curve & the medium NDVI class with the light green curve. The appended table shows the standard deviations for the monthly mean NDVI values calculated across the years.

Table 2. Range in seasonal areal coverage mean values (2001-2012).

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<tr>
<th>Area of interest</th>
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<th>Range in high-NDVI class's areal coverage values (%)</th>
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<td>Highland</td>
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<td>23</td>
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<td>1KB8</td>
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</table>
4.4. Correlation between NDVI-class’s areal coverage variation & precipitation

The relationship between past precipitation and vegetation coverage was studied through calculation of Pearson’s correlation coefficient. Table 4 shows the selected NDVI-classes’ seasonal (rainy, lag-1, lag-2) areal coverage variability with respect to precipitation in two time periods that are representing the years 2001-2010 and 2004-2010. Separate analysis for the latter time period is considered due its similarity with past precipitation, which can be confirmed by observing the plots in figure 7.

Table 4. Pearson correlation (r) between mean NDVI areal coverage values for rainy (March-April-May), lag in growth-1 (June-July-August), lag in growth-2 (August-September-October) and precipitation (2001-2010) from the study area.

Note: the statistically significant coefficients are underlined.
5. Discussion
Statistical analyses were conducted on the data extracted from the NDVI images in an attempt to derive trends and patterns from the various datasets and to see if it is possible to establish inter-annual relationships with the hydrological data from the study area. As discussed in the methodology section the Kilombero River Catchment was divided into three parts based on topography and the presence of runoff data. The following discussions take this into consideration when presenting the findings.

5.1. NDVI pattern for Naturally Vegetated Wetland (NVW)
The naturally vegetated wetland land-cover class is situated in the lowest parts of the Kilombero river valley and forms part of the floodplain in the area. This flood plain is reported to be flooded annually during the wet season with water depths reaching several meters. With the exception of the river channels and river banks, permanent swamps and permanent water bodies, the largest part of the floodplain dries up during the dry season from mid-May until mid-November, with water levels dropping quite smoothly. Usually, peak water levels are observed in March and April but in some years, these peaks can also occur as early as in January (Scheibler, 2012). These patterns show similarity to the NDVI value plot given in Figure 6. From the figure it can be observed that the peak NDVI values are attained in the rainy months of March, April and May demonstrating the strong relationship that exists between the vegetation and precipitation in the naturally vegetated wetland area. After the peak values are attained there is a smooth decrease in NDVI values into the drier months of September and October.

The yearly mean NDVI values' variation in the naturally vegetated wetland area rather shows a weak trend between the years 2001 and 2010 (see figures 7(a) & 7(b)). Although the time series is short, a significant correlation exists between the two data sets in the years between 2004 and 2010. This could provide additional information in the attempts being made to evaluate the accuracy of the precipitation data from the area.
5.2. Seasonal areal coverage variations of the medium and high-NDVI classes

Appendices 2-13 and figures 11(c)-13(c) respectively show the seasonal variability of the selected NDVI classes’ areal coverage for the individual years and the mean values for the time period considered in the areas of interest. The yearly as well as mean areal coverage variability plots of the high-NDVI class attained peak values in the rainy months of March-April-May in the same manner as the seasonal NDVI values’ variability plots for the Naturally Vegetated Wetland (NVW) area (see figure 6). Meanwhile the corresponding values for the medium-NDVI class shown to increase after each year’s rainy season. The reversed seasonal trends for the high and medium-NDVI classes are observed not only for the lowland area but also for the highland and sub-catchment 1KB8. Although similar patterns noticed in all areas of interest, the highest seasonal areal coverage variability for the high and medium-NDVI classes is noted in the lowland area. This can be confirmed with table 2 that represents the range in areal coverage values extracted from figures 11(c), 12(c) and 13(c). Further observations on figure 6 and appendices 2-13 indicate the relatively higher sensitivity of the selected NDVI classes in the lowland area to seasonal changes. This conforms to the initial assumption about the importance of the lowland and its sub-catchment (1KB17) in describing the Kilombero’s hydrology. It should also be noted that in the area the annual flooding raises the water levels between November and April with most of the peak flows occurring in March-April (RIS, 2002).

The highland and sub-catchment 1KB8 mean areal coverage datasets show relatively more similarities with each other than each do to the lowland area. This can be seen from table 2 with the range values and in table 3 with the correlation coefficients between the areas of interests. The NDVI images as well as graph plots in appendices 2-14 show that the high-NDVI class areal coverage in the highland area and 1KB8 remain relatively higher than the lowland area in the dry season (October images). These could be due to the sustained greenness of the forested highland areas. Meanwhile the medium-NDVI classes mean areal coverage starts to decrease after its peak in August in the lowland area overlapping with the agricultural growing seasons in Kilombero.
5.3. Inter-annual areal coverage variations of the medium and high-NDVI classes

As discussed in the methodology section the analysis was focused on the inner-annual and inter-annual areal coverage variation of the medium and high-NDVI classes in the highland, lowland and sub-catchment 1KB8. The NDVI-classes’ mean areal coverage for the rainy (March-April-May), growth lag-1 (June-July-August) and growth lag-2 (August-September-October) seasons were calculated and comparisons were made with the annual precipitation averages between 2001 and 2010 via calculations of Pearson’s correlation coefficient. Visual observation of the precipitation and NDVI curves revealed a close relationship between the two parameters especially after the year 2004. This laid the basis to further calculate separate coefficients for this time period 2004-2010, although the time series is short (See the table attached with figure 7).

The NDVI classes’ areal coverage shows both negative and positive correlation with precipitation. Effects related to lags in vegetation growth as well as the particular time range chosen in calculating the coefficients can also be observed in table 4. The high-NDVI class in the lowland area has the highest correlation (both positive and negative) with the precipitation in the catchment. Interestingly, the mean values taken at latter part of the year (vegetation growth lag-2), show positive correlation with precipitation after 2004 in all areas of interest (See the underlined coefficients in Table 4). The high-NDVI class’s correlation with precipitation gradually increases positively (after 2004) as the time gap from the rainy seasons increase. Meanwhile the medium-NDVI class shows mostly negative correlation with the precipitation in the highland and 1KB8 but in the lowland meaningful relationships between the coefficients could not be established. In general, there is low correlation between the yearly precipitation and the medium-NDVI class’s mean areal coverage in the rainy months (March-April-May) of the years 2001-2010. But in latter periods of the years the negative correlation increased.
Appendix 1 shows the runoff data available for sub-catchment 1KB8. It was hypothesized that comparison of the available runoff data in the sub-catchment with NDVI can enable partial capture of the effect of the climatic and environmental variability on the functioning of a catchment (Dezetter and Ruelland, 2010). Figures 14(a) and 14(b) respectively show the runoff and the areal coverage variability of the selected NDVI classes for the rainy months in the years 2001-2010. Correlation coefficients of 0.12 and -0.23 obtained for the medium and high NDVI classes respectively, when comparisons were made with respect to the runoff dataset. Since 1KB8 shows similar areal coverage variation as the highland (See table 3), the low degree of correlations that exist between the NDVI classes’ areal coverage variation and the runoff might also be valid for the whole highland area. Meanwhile trend lines and the corresponding R-square values for runoff and selected NDVI classes’ areal coverage datasets are presented in figure 14. All the R-square values are low but the trend lines for the two show slight similarities. It should be noted that the runoff data has 46% missing data.

5.4. NDVI trends and patterns

This study aims to predicting future hydrological trends from mean annual NDVI-values and selected NDVI-classes’ areal coverage variability. The trend lines with their corresponding R-square values are presented within figures 7-10. It can be observed in figure 7 that the yearly mean NDVI plot’s trend line has a low R-square value in the years 2001 to 2010 and it is decreasing through the years. Meanwhile NDVI-classes’ areal coverage in the areas of interest shows different R-square values for the 3 periods considered in each year (rainy season, growth lag-1 and growth lag-2). Much of the high R-square values are observed for the NDVI classes in the lowland area, particularly in the
medium NDVI class’s June-July-August mean where an increasing trend that gave an R-square value of 0.27.

The observed low R-square values and the associated uncertainty in detecting trends and trend changes can be related to increasing inter-annual variability in NDVI values. According to Forkel et al. (2013) inter-annual variability of NDVI time series can be caused by artifacts from the harmonization of a dataset from different sensors, meteorological distortions like clouds or snow and environmental processes such as climate patterns or disturbances. Sensor degradation varied by spectral band, view angle, and mirror side can also have effect (Wang, et al., 2012). Meanwhile Tucker and Anyamba (2001) described El Niño Southern Oscillation (ENSO) as one climatic factor that can influence NDVI trend detection efforts.

Lowland and highland are the two areas of interest created as a result of the topography based classification of the river catchment. The chosen NDVI classes’ areal coverage variation pattern in the two topographic classes shows both similarities and differences. The high NDVI class in both areas attains peak values in the rainy seasons and gradually decreased to the dry seasons displaying a similar pattern in all the years considered in the study (See figures 11-13). Meanwhile the high NDVI class negatively correlated to the annual precipitation in the rainy seasons and positively to the latter (drier) part of the year (See table 4). These contradictory relations might be associated with the uncertainty that exists in the precipitation data. Meanwhile the medium-NDVI class’s mean yearly plot shows a smooth reduction after attaining peak value in August only for the lowland area (See figure 13(c)). Here NDVI’s response to agricultural practices should be considered since Kangalawe and Liwenga (2005) reported an increased use of the wetland (lowland) area for agriculture during the last 20 years due to population growth and the resulting need for more food. Furthermore Tanner & Lukmanji (1987) pointed that August marks the harvesting month in the Kilombero catchment, which might explain the reduced greenness (low NDVI value) in post-harvest months of September and October. Meanwhile the
observed increase in the medium-NDVI class’s areal coverage in the pre-harvest months of June-July-August overlaps with the agricultural growing season in the area.

6. Conclusion
In this study various statistical analyses were conducted on the data extracted from the NDVI images in an attempt to determine trends and establish relationships with the hydrology of the area. There was a clear shift in NDVI values between wet and dry seasons indicating an increase in “greenness” in the valley during the wet seasons and a subsequent shift in coverage during the dry season. While the NDVI analyses were able to capture some of the relationship that exists between vegetation and seasonal changes in the study area, there were less clear relations between the NDVI analyses and the hydrologic response at inter-annual time scale. Similar studies pointed out that error related to the harmonization of a dataset from different sensors; meteorological distortions like clouds or snow and environmental processes such as climate patterns or disturbances can pose problems in trend detection. Sensor degradation should also be taken into consideration. Although accurate future trends cannot be established from the data at hand, it was possible to observe some strong correlations between NDVI with past precipitation (figure 7 and table 4).

The main uncertainty in the inputs used in the study is related to lack of rigor in the hydrological data. Similar situation encountered in another study from the area. Furthermore the land cover data used in the study could have been more reliable if field work had been done to investigate what is on the ground. Use of vegetation indices other than NDVI should have been considered in the study. Lastly it should be mentioned that further study is necessary to better understand the connection between land cover and hydrologic response in this part of Africa.
References


CHARACTERIZATION OF PLANT-WATER INTERACTION IN KILOMBERO RIVER CATCHMENT IN TANZANIA USING NORMALIZED DIFFERENCE VEGETATION INDEX (NDVI)


CHARACTERIZATION OF PLANT-WATER INTERACTION IN KILOMERO RIVER CATCHMENT IN TANZANIA USING NORMALIZED DIFFERENCE VEGETATION INDEX (NDVI)


Appendix-1

Available hydrological data from Kilombero.

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Appendix-2
Spatio-temporal variation of NDVI in 2001 in the study area. NDVI image wet season (April) (a). NDVI image dry season (October) (b). Monthly (March-to-October) areal coverage variation of the medium (light-green curve) and high (dark-green curve) NDVI classes in the highland (c), Lowland (d) and sub-catchment 1KB8 (e).
Appendix-3

Spatio-temporal variation of NDVI in 2002 in the study area. NDVI image wet season (April) (a). NDVI image dry season (October) (b). Monthly (March-to-October) areal coverage variation of the medium (light-green curve) and high (dark-green curve) NDVI classes in the highland (c), Lowland (d) and sub-catchment 1KB8 (e).
Appendix-4

Spatio-temporal variation of NDVI in 2003 in the study area. NDVI image wet season (April) (a). NDVI image dry season (October) (b). Monthly (March-to-October) areal coverage variation of the medium (light-green curve) and high (dark-green curve) NDVI classes in the highland (c), Lowland (d) and sub-catchment 1KB8 (e).
Appendix-5

Spatio-temporal variation of NDVI in 2004 in the study area. NDVI image wet season (April) (a). NDVI image dry season (October) (b). Monthly (March-to-October) areal coverage variation of the medium (light-green curve) and high (dark-green curve) NDVI classes in the highland (c), Lowland (d) and sub-catchment 1KB8 (e).
Appendix-6

Spatio-temporal variation of NDVI in 2005 in the study area. NDVI image wet season (April) (a). NDVI image dry season (October) (b). Monthly (March-to-October) areal coverage variation of the medium (light-green curve) and high (dark-green curve) NDVI classes in the highland (c), Lowland (d) and sub-catchment 1KB8 (e).
Appendix-7

Spatio-temporal variation of NDVI in 2006 in the study area. NDVI image wet season (April) (a). NDVI image dry season (October) (b). Monthly (March-to-October) areal coverage variation of the medium (light-green curve) and high (dark-green curve) NDVI classes in the highland (c), Lowland (d) and sub-catchment 1KB8 (e).
Appendix-8

Spatio-temporal variation of NDVI in 2007 in the study area. NDVI image wet season (April) (a). NDVI image dry season (October) (b). Monthly (March-to-October) areal coverage variation of the medium (light-green curve) and high (dark-green curve) NDVI classes in the highland (c), Lowland (d) and sub-catchment 1KB8 (e).
Appendix-9

Spatio-temporal variation of NDVI in 2008 in the study area. NDVI image wet season (April) (a). NDVI image dry season (October) (b). Monthly (March-to-October) areal coverage variation of the medium (light-green curve) and high (dark-green curve) NDVI classes in the highland (c), Lowland (d) and sub-catchment 1KB8 (e).
Appendix-10

Spatio-temporal variation of NDVI in 2009 in the study area. NDVI image wet season (April) (a). NDVI image dry season (October) (b). Monthly (March-to-October) areal coverage variation of the medium (light-green curve) and high (dark-green curve) NDVI classes in the highland (c), Lowland (d) and sub-catchment 1KB8 (e).
Appendix-11

Spatio-temporal variation of NDVI in 2010 in the study area. NDVI image wet season (April) (a). NDVI image dry season (October) (b). Monthly (March-to-October) areal coverage variation of the medium (light-green curve) and high (dark-green curve) NDVI classes in the highland (c), Lowland (d) and sub-catchment 1KB8 (e).
Appendix-12

Spatio-temporal variation of NDVI in 2011 in the study area. NDVI image wet season (April) (a), NDVI image dry season (October) (b). Monthly (March-to-October) areal coverage variation of the medium (light-green curve) and high (dark-green curve) NDVI classes in the highland (c), Lowland (d) and sub-catchment 1KB8 (e).
Appendix-13

Spatio-temporal variation of NDVI in 2012 in the study area. NDVI image wet season (April) (a). NDVI image dry season (October) (b). Monthly (March-to-October) areal coverage variation of the medium (light-green curve) and high (dark-green curve) NDVI classes in the highland (c), Lowland (d) and sub-catchment 1KB8 (e).