EFFECT OF HYDROLOGY ON HABITAT AREA IN AN INLAND WETLAND:

UPSTREAM DISCHARGE VS EXTENT OF GREENESS IN THE OKAVANGO DELTA, BOTSWANA

by

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ABSTRACT

The annual flood cycle in Botswana's Okavango Delta is a critical factor in the biodiversity and extensive populations of charismatic wildlife, which sustain a thriving tourism industry. Floodwater originates as precipitation hundreds of kilometers away and is subject to natural losses and human diversion in Angola and Namibia before reaching the Delta. However, increasing populations and corresponding agriculture and industry in these countries has put increased pressure on the Delta's limited water resources, necessitating a clear understanding of how streamflow influences ecosystem processes and services. Therefore, I conducted a multi-year analysis of streamflow data from gauges near the upstream entrance and downstream exit of the Delta combined with a remote sensing analysis of four subareas within the Delta to evaluate the relationship between stream flow, and visually evaluated extent of vegetation and normalized vegetation density index (NDVI). NDVI is a common quantitative measure for green vegetation coverage within a landscape which can also be used as an indicator for extent of habitat available to wildlife. NDVI was higher in years with high flows into and out of the delta than in years with low flows. NDVI is more strongly correlated to stream flow out of the Delta than to streamflow into the Delta, suggesting that water available for flooding is a key driver of green vegetative cover and therefore habitat availability for wildlife. My subjective evaluation of imagery found more consistent differences in vegetation extent between high, medium, and low flow years, suggesting that other approaches to quantitative image analysis might show stronger relationships between hydrology and habitat than NDVI.

INTRODUCTION

The Okavango Delta, a large, low-gradient alluvial fan (Stanistreet and McCarthy 1993) located in northwest Botswana is Southern Africa's largest wetland, with 4,000 km^2 of permanent wetland and expanding to as much as 12,000 km^2 during peak flood season. The source catchment is in the highlands of Angola and water is transported via the Okavango River into northern Botswana, where it empties into the Kalahari Desert, forming a vast and dynamic wetland comprised of ever-changing channels, swamps, islands and floodplains (McCarthy and Ellery, 1998).

Figure 1: Location of the Okavango catchment and watershed

Home to 1,300 taxa of plants, 444 species of bird, 71 species of fish, 64 species of reptiles and 122 species of mammals, including large populations of the larger, "charismatic" species (Ramberg et al. 2006), the Okavango is one of the region's most important destinations for ecotourism (Kgathi et al. 2006) which accounts for 4.5% of Botswana's GDP (Milzow et al. 2009). Much of the human population within the vicinity of the Delta is dependent on tourism for their livelihood (Barnes et al. 2002). It is one of the World Wildlife Federation's (WWF) top 200 eco-regions of global significance, and is one of the world's largest Ramsar sites (Hughes et al. 2011). The Ramsar site consists of 6,684,000 ha encompassing the Okavango River, the Okavango Delta, Lake Ngami, and parts of the Kwando and Linyati River systems, with a transition zone extending to Angola's Bie Plateau. (Swatuk 2003). The large size of the Delta undoubtedly contributes to its species richness. It is well documented that as the area of a habitat increases, the number of plant and animal species increases in a near-logarithmic manner (MacArthur and Wilson, 1963).

Hydrological conditions have been shown to influence biodiversity via the spatial pattern of carrying capacity, niche habitat structuring, and species' dispersal mechanisms for a variety of species (Konar et al. 2013). The continuous physical variation along a river system presents a gradient of conditions to which the resident biota adapt and re-adapt (Vannote et al. 1980), producing a highly diverse grouping of species and environmental processes related to variable flood regimes and unique channel processes (Naiman and Descamps, 1997). Accordingly, much of the biodiversity in the Okavango Delta can be attributed to the continual shift in distribution of water within the Delta and the resulting "mosaic" of niche habitats caused by the process of channel aggradation and failure. Under these circumstances, each microhabitat is in an ongoing state of flux and climax communities rarely develop (McCarthy 2006). This spatial heterogeneity and temporal fluctuation helps to maintain the richness and complexity of the ecological community, including consumers and predators at higher trophic levels (Power et al. 1995). In addition to their role in channel forming dynamics, flood pulses have been shown to support a range of biota adapted to exploit parts of the flood cycle and survive through the others (Junk et al. 1989). For example, because of frequent flooding, primary floodplains are mainly colonized by grasses, which in turn are an important food source that sustain the large herbivore (and therefore large carnivore) populations that are the main attraction for the tourism business (Mizlow et al. 2010). Flooding is also important for many of the Okavango’s fish species, as flooding connects channels supporting migration and spawning (Merron and Bruton, 1995). Because the area around the Delta has never been extensively settled and water development projects have not affected its hydrology (McCarthy and Ellery, 1998) the Delta retains its natural flow regime, a factor which has been shown to play a critical role in in sustaining native biodiversity and ecosystem integrity (Poff et al. 1997).

The Okavango River and Delta support a broad group of stakeholders with varying interests and priorities for use of the Delta (Magole, 2008). Falling between the political boundaries of Angola, Namibia and Botswana, significant international cooperation is required to maintain its pristine nature while also providing for the increasing water needs of populations in the surrounding areas (Magole 2008). This balance and cooperation will help to avoid risks of violent conflict (Mbaiwa 2004), support appropriate distribution of the economic benefits of the Delta (Kgathi et al. 2006) and protect the interests of people who depend on the Delta for their livelihood (Magole 2009). Conflicts so far have been verbal, particularly between Botswana, which relies on the tourism cash flow from the Okavango Delta, and Namibia which increasingly looks to the Okavango River as a potential source of freshwater and energy (Mbaiwa 2004). However, following 27 years of Civil War in Angola, the Okavango watershed now faces additional pressure from increasing population, urbanization, and agriculture in the primary catchment area (Ellery and McCarthy, 1994).

As human populations advance in the region, demands on the water resources within the Okavango watershed are likely to increase. At the same time, tourism is also highly dependent on habitat-sustaining water resources and is likely to remain an important contributor to local economies. To enable cooperative management, fact-based trade-off analyses and sustainable decision making, it is necessary to have a solid understanding of the ecological impacts of potential changes to water flow into and around the Delta. Much work has been done to estimate the impact of external changes on flow into the Delta (e.g. Andersson et al. 2003 and 2006, Hughes et al. 2006), flow within the Delta (e.g. Bauer et al. 2006, Dincer et al. 1987), extent of flooding (e.g. Wolski et al. 2006 and 2014, Gumbricht et al. 2004) and flow out of the Delta (e.g. Gieske et al. 1997). While there is continuing progress on the effectiveness of models used for these analyses, both the direction and magnitude of projected change differ between models (Hughes et al. 2011) and modeling the Okavango's highly complex hydrologic system is an ongoing effort.

Studies have begun to connect hydrologic variation with vegetation response and the inferred linkage with animal populations (e.g. Murray-Hudson et al. 2006, Milzow et al. 2010). Milzow et al (2010) used remote sensing data from Landsat TM to model patch-level vegetative responses to a variety of hydrologic scenarios. To understand landscape scale vegetative responses, other studies have investigated the connection between precipitation and Normalized Difference Vegetation Index (NDVI) and rainwater in the region, but have excluded the Okavango Delta, noting that within the Delta NDVI is linked to flooding as opposed to precipitation (Gaughan et al. 2012). NDVI has been established as an important tool for estimating distributions of herbivores and associated species (e.g. predators) and is viewed as crucial to understanding impacts of climate and other changes to habitats (Pettorelli et al. 2011). No studies have specifically linked decade-scale variations in flow regime in the Okavango Delta to landscape-scale habitat availability.

Therefore, my study aims to provide a starting point to filling this gap, leveraging NDVI as a proxy for habitat quantity and quality by addressing the following research question: Is annual variation in discharge from the Okavango River directly linked to spatial variation in vegetation in the Okavango Delta? The guiding hypothesis is: Spatial extent of green vegetation increases in times of higher flow because flooded areas are larger, supporting plant growth in areas that have inadequate water in drier years. With sufficient observations at varying levels of water flow, I anticipate that the area of green vegetation will increase with annual and seasonal volume of river discharge.

The specific objectives of my study are to:

1. Characterize and quantify: 1) total annual streamflow volume in and out of the Delta, 2) volume during the core runoff season, 3) sustained peak flows during the core runoff season, 4) speed at which water moves through the Delta, and 5) patterns of water delivery to the outer reaches of the Delta

2. Determine spatial extent and density of vegetation, as measured by greenness/NDVI during wet and dry years

3. Evaluate whether variation in vegetation patterns can be related streamflow variation to enable predictive modelling.

METHODS

Study Area and Watershed Description

The **Okavango Delta**, Africa's largest wetland, exists as a result of the Okavango River emptying an average of 9.2 km^3 of water each year onto the northern Kalahari Desert. The permanent wetland is around 4,000 km^2 in size and can expand to as much as 12,000 km^2 during peak flow season. As can be seen in Figure 2, water for the Delta originates in the highlands of Angola, where the runoff from seasonal rains form the Cuito and Cubango Rivers. These rivers unite near the border of Angola and Namibia to form the Okavango River which carries the water to the Okavango Delta (McCarthy and Ellery, 2008).

Figure 2: The Okavango Catchment. Rains in the Angolan highlands (upper left) feeds the Cubango and Cuito Rivers, which combine to form the Okavango River. The Okavango River empties onto the Kalahari Desert, forming the Okavango Delta (lower right)

The Okavango Delta's "lush riverine forests, dry woodland, and extensive sedge and grass covered swamplands and clear waterways" are clearly distinguished from the surrounding semi-arid savanna. Geologically, the Delta is situated in a depression between two uplifting and southwesterly propagating arches of basement rock (McCarthy, 2006). For the purposes of this study, the Delta is defined as the area between Mohembo, at the border of Namibia and Botswana, and Maun, 250 km to the southeast. Mohembo and Maun are near the natural upstream and downstream boundaries of the Delta and are where the two main stream gauges used in this analysis are located. The Delta consists of two parts: (1) the *panhandle* is a narrow entry corridor, possibly representing a graben structure with elevated margins which restricts the width of the river flood plain; (2) the *alluvial fan* below the Gumare fault, where the flood plain loses confinement and spreads out over a gently sloping conical surface (McCarthy, 2006).

Figure 3: The panhandle and alluvial fan of the Okavango Delta

Below the panhandle, the Delta splits into several distributary channels creating the classic Delta shape: the **Thaoge** directs water to the west, the **Jao-Boro** directs water to the south, the **Selinda** directs water to the north east and the **Nqoga-Maunachira** directs water to the south east (Gumbricht, 2004).

My study evaluates changes in hydrologic and vegetative patterns at the scale of the entire Delta and at the scale of four smaller areas within the Delta (figure 4). These areas were selected to represent the major distributary channels of the Delta. The specific boundaries used for image analysis were based on fit within a single Landsat TM image to enable consistent analysis.

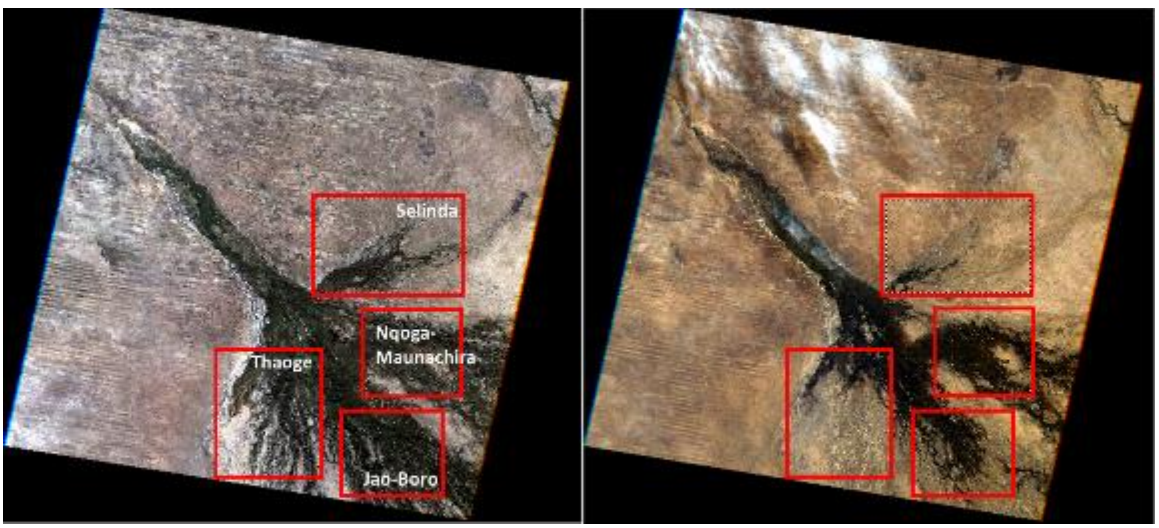


Figure 4: Satellite images showing the Okavango Delta in wet and dry years, with the four major distributary channel areas identified (images adapted from GLOVIS)

Water entering the Delta:

Water enters the Delta via runoff from the Okavango River, and through local rainfall over the Delta. Hydrological inputs into the Delta vary considerably, mainly driven by long- and near-term cycles in climate (McCarthy et al. 2000). The climate of

Angolan highlands is characterized by a pronounced annual cycle with a wet season from October through March during which, in recent years, precipitation has averaged 6 mm/day (Hughes et al. 2011). Although data are somewhat sparse because of the civil war in Angola (Wilk et al. 2006), it is clear that rain falls in the catchment between December and March and peak discharge from the Okavango River into the panhandle occurs in April (Wilson and Dincer, 1976). Total annual discharge varies considerably and over the past 60 years the minimum annual discharge was 6.0×10^9 m^3 and the maximum was 16.4×10^9 m^3 (Gumbricht et al. 2004).

Multi-decadal wet and dry phases in terms of runoff have been attributed to multi-decadal cyclic oscillations in precipitation (Wolski et al. 2012). The basin has been subject to three general wetness regimes in the recent past: wet (1974-1985), transitional (1985-1990) and dry (1990-2000) (Murray-Hudson, 2006). Based on a preliminary review of the data used for this study, it appears that since 2000 flows into the Delta have been increasing. In addition to precipitation in the catchment, local rainfall, derived mainly from scattered and variable convective thunderstorms between October and May, contributes significantly to the hydrology of the Delta (McCarthy, 2006). Rainfall ranges from 288.3 mm to 1144.5 mm, with an average of 513 mm, resulting in 6×10^9 m^3 of water being delivered to the Delta each year (McCarthy et al. 1998).

Sediment and Channel Dynamics

Most of the catchment is underlain by sand which has been transported and reworked as bedload (Murray-Hudson, 2006). There is very little suspended silt or mud as the system is almost completely absent of weathering bedrock and dissolved solids and nutrients are very low (McCarthy, 2006). Approximately 170,000 tons of bedload, 39,000 tons of suspended sediment and 360,000 tons of solutes are delivered to the Delta each year. The channel banks are permeable and water constantly leaks from the channels to the adjacent wetlands dispersing fine sediment to the permanent swamps. The sand remains trapped in the channels and is deposited on the channel beds, resulting in aggradation and eventual failure and shifting of the channel banks. (McCarthy and Ellery, 1998). Primary channels aggrade vertically as a result of bedload deposition. The rate of aggradation increases down channel and may exceed 5 cm/year in the distal reaches. Rapid aggradation is associated with a decline in flow velocity, which initiates a series of feedback mechanisms including invasion of the channel by aquatic plants which trap floating plant debris, further reducing flow rate and causing the channel surface water to become elevated. This increases the water loss in the channel, accelerating the blockage and aggradation. The channel eventually fails. Enhanced water loss from the channel promotes the growth of swamp vegetation, which confines the failing channel. Increased flow through the swamp erodes existing hippo trails, producing a secondary channel system which overlaps but does not connect directly to the failing reach of the primary channel. The region of failure of the primary channel migrates up stream, accompanied by the propagation of the secondary channel system. The swamp distal to the failed primary channel desiccates and is destroyed by peat fires (McCarthy et al 1992). Peat is the only material which builds up in these areas (Ellery et al. 1989) and there is a higher frequency of fire in the wetland than in surrounding dry areas because of this fuel buildup (Heinl et al. 2006). It is worth noting that this process of constant channel aggradation is a significant contributor to the Delta's biodiversity. The constant shift in distribution of water and surface results in a "mosaic of habitats" in different stages of wetting and drying where climax communities rarely develop (McCarthy, 2006).

Channel width, dominated by vegetative processes, varies depending on relative discharge throughout the Delta, while channel depth and current velocity remain generally constant across the range of discharges (Ellery et al. 2003). The channel depth in the upper panhandle is between 2 and 3 m, increasing to 4 m at the lower and, and depth gradually declines down the alluvial fan. During the peak flow season, the channel system cannot contain the seasonal floodwater, which spreads laterally over a wide area to form the seasonal swamps of the lower Delta. This water is eventually lost to ground water seepage and, primarily, to evapotranspiration (McCarthy et al 1991).

Vegetation and Evapotranspiration

Because the river carries little silt, the river banks are primarily comprised of vegetation consisting of a lower layer of peat, stabilized by rhizomes and roots on which grasses and sedges form the upper layer (McCarthy, 2006). Much of the water flow permeates through the swamps which consist of vegetation rooted in a substrate of partially decomposed plant material normally in excess of 1-m thick. *Cyperus papyrus*, a giant sedge, dominates the vegetation of the perennial swamp, with subordinate *Phragmites* spp. and *Miscanthus junceus*. The roots and rhizomes of these plants stabilize the substrate, particularly on the channel margins, which are vertical to overhanging (McCarthy et al. 1988).

The exit side of the Delta's water balance equation is dominated by loss from evapotranspiration (Murray-Hudson, 2006) which removes 95% of incoming water (Dincer et al. 1981). Evapotranspiration has been estimated to range from 0.06 to 4.3 mm/day with considerable variation depending on soil characteristics and vegetative cover (Bauer et al. 2004). Channel margins in the Delta are generally permeable, enabling transfer of both surface and ground water from the channel to swamps and islands (McCarthy et al. 1989). Islands have been shown to play an important role in the structure and functioning of the Delta because of their role in cycling water and nutrients. As ground water is taken up by plants for evapotranspiration, dissolved nutrients remain in the water (McCarthy et al. 2012). Vegetation is most sensitive to water levels at each species optimal rooting depth (Milzow et al 2010), as such, islands show a concentric vegetation zoning, with an outer circle generally comprised of riverine forest consisting of evergreen trees, a second ring towards the center dominated by deciduous trees, followed by grass and shrubs, then open grassland and finally barren soil (Ellery et al. 1993). Like other dryland parts of the ecosystem, water availability is the most important climate constraint on plant growth (Prince et al 1995). The island vegetative gradient is caused by plant competition for water permeating from channels, as the water moves to the center, it becomes increasingly concentrated until it is too saline rich for vegetation (Ellery et al. 1993).

Seasonal Flooding

A pronounced annual flood pulse results from seasonal rains in the Angolan headwaters. The arrival of seasonal flood causes stage rise of in the panhandle section of the Delta of up to 2 m because of the locally confining geologic margin. In the channels of the permanent wetland, stage rise is only 15-20 cm. Average water depth in the permanent wetland is approximately 1.5 m and 30 cm in the seasonal wetlands (McCarthy, 2006). The pronounced annual flood pulse results from seasonal rains in the Angolan headwaters, causes expansion and contraction of the flooded area and is a primary driver of the vegetation ecology of the Delta (Murray-Hudson et al. 2006). The Annual flood wave takes 4-5 months to traverse the fan and maximum inundation usually occurs in August (mid-winter) (Gumbricht et al. 2004). The flood expands out from the fringes of the permanent swamp by a combination of channel and sheet flow (Gumbricht et al. 2004).

The seasonal flood advances very slowly, taking 4 months to progress the 250 km from Mohembo to Maun (McCarthy and Ellery, 2010). Four primary reasons have been identified for this slow flow: First, the alluvial fan of the Okavango has the lowest gradient (1:3500 on average) of any alluvial fan yet described (McCarty et al. 1991). Second, the flood advance is impeded by vegetation, third, the topography is undulating and flood can only advance once deeper depressions have been filled and finally, much of the flood water is lost to ground water recharge (McCarthy and Ellery, 2010).

Groundwater

Soils of the Delta are sandy and have a high hydraulic conductivity, so flood advance is accompanied by recharge of groundwater (McCarthy, 2006). Advancing floodwater encounters dry ground and infiltrates, raising the groundwater level. The depth of the groundwater table is a significant factor in the overall hydrology of the Delta because the area of seasonal flooding can be influenced by the amount of water which is needed to recharge. The amount of recharge needed is generally a factor of recent precipitation and quantity of runoff water supplied (McCarthy et al. 2000). Precipitation contributes to ground water and therefore can influence flooding by decreasing the amount and timing of runoff water required to raise the water table to the surface (McCarthy et al 1998).

The water table below the Delta is shallow and deepens away from the wetland. The slope of the water table is steep on the western side of the Delta and flattens to the south, and the overall shape suggests a large groundwater recharge mound centered on the Delta (McCarthy, 2006). While less than 2% of the inflow leaves as groundwater flow (Wilson and Dincer, 1976), interaction between the surface water and ground water strongly influences the structure and function of the wetland ecosystem (McCarthy, 2006).

Overview of Study Approach

The overarching goal of my study was to understand the relationship between hydrology and availability of wildlife habitat in the Okavango Delta. For the purposes of this study, “habitat” has been identified as areas with vegetation, which is contrasted with the rock and sand of the surrounding Kalahari Desert. To characterize this relationship, I analyzed patterns of stream flow, measured at stream gauges, and patterns of greenness, measured with remote sensing, and explored the relationship between streamflow and green vegetation was explored.

Hydrology Analysis

Stream Gauge Data for the Okavango Delta were obtained through an online resource made available to the public by the Okavango Research Institute (ORI), which is part of the University of Botswana. Data were available for many gauges within the Delta, in some cases dating as far back as the 1930s (with gaps). Long-term daily and monthly discharge data, dating back to December 1974 are readily available for the Mohembo Water Station Gauge at the upstream entrance to the Delta and for the Maun Bridge Water Gauge at the downstream end of the Delta (University of Botswana, 2020). The long-term stream flow records for these two gauging stations also encompassed the period of available remote sensing data.

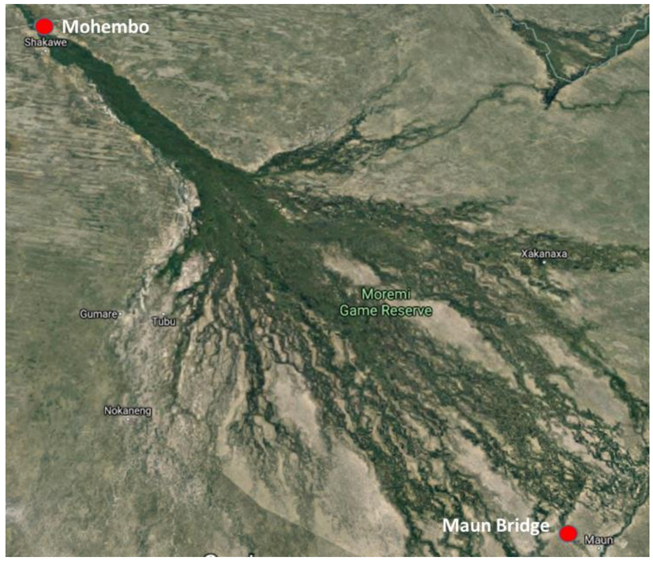


Figure 5: Location of water gauge stations within the Okavango

Stream flow data from the Mohembo and Maun Bridge water gauge stations were analyzed to provide a quantitative view of the distribution and timing of water delivery across the Delta at a range of flows. There are generally five critical components of flow regime which regulate ecological processes in channel systems: the magnitude, frequency, duration, timing and rate of change (Poff and Ward, 1989). Accordingly, my analysis characterized and quantified the hydrological measurements detailed below.

Total annual streamflow volume in and out of the Delta: To compare variation across years and contrast high and low-flow years, total annual volume of flow in and out of the Okavango Delta was assessed. First, the full dataset was downloaded for each of the stream gauges. Next, a hydrograph was created for each stream gauge by plotting daily discharge vs. time for the time period 1975 through 2011. These years were chosen because both gauges had consecutive and nearly complete data for this time period. This also fit well with the time period for which remote sensing data were available. The data were then combined into a single pivot table in Excel, from which the remaining analyses were performed. Total annual streamflow for each year was calculated as the sum of the daily stream flows, which were calculated by multiplying the daily streamflow rate by 86,400 to convert from m^3/second to m^3/day. The year 1978 was a significant outlier in terms of streamflow because it showed a protracted period of peak flows. A literature search did not reveal any causes for this, so the data points for 1978 were replaced with the average of the two prior and two subsequent years. Total annual streamflow for Mohembo vs. Maun Bridge was plotted to determine high, medium and low flow years, which was later used to select years for comparison in the remote sensing analysis.

Volume during the core runoff season: In an effort to understand timing and volumes of water available for flooding it was necessary to define and characterize a core runoff season. The core runoff season refers to the seasonal period when river flows entering the delta are distinctly elevated and contribute disproportionately to annual inputs. Total monthly discharge at Mohembo was calculated for each month of the analysis period by summing daily discharge for each month. Monthly discharge was plotted for each year in the study period. Next, monthly discharge as a percentage of total annual discharge was calculated and plotted. The cumulative monthly discharge (as a percentage of total annual discharge) was also plotted. Based on this analysis, and as explained in the results section, a core March-May runoff season was defined for the Okavango Delta, and total runoff for the core runoff season was calculated for each year.

Core season runoff was compared with total annual runoff to determine the extent to which these two variables are related.

Sustained peak flows during core runoff season: To better understand the pulse of water entering the Delta, the duration of peak flows within the core runoff season were assessed for each year of the study period. Daily discharge for the entire core runoff season was plotted for each year in the study period. Daily values were then converted into percentage of total discharge for each year's core runoff season. "Peak flow days" were defined as including the individual day with the highest percent of total seasonal runoff (the actual peak) and the adjacent, consecutive days which were 1% less of the total season runoff than peak. Sustained peak flow was defined as the number of consecutive days at which peak flow, as defined above, was maintained.

Speed at which water moves through the Delta: To evaluate the how quickly floodwaters reach the distal areas of the Delta, the speed of water travel was estimated. Daily discharge was plotted for both the Mohembo and Maun Bridge stream gauge and the dates of peak runoff were determined for each year in the study period. The time (in days) was calculated between peak discharge at Mohembo and peak discharge at Maun Bridge. This time value was then divided by the distance between the two water gauge stations (250 km) to determine a speed (km/day) of peak travel for each year.

Patterns of water delivery to the outer reaches of the Delta: The annual flow rates from the above calculation were used in combination with distance measurements to assess timing of peak flows to four other parts of the Okavango Delta (Selinda, Nqoga-Maunachira, Jao-Boro and Thaoge). Distances between Mohembo and proximal and distal points within each area were calculated using the NOAA coordinate distance calculator (Williams, 2020). These distances (km) were multiplied by the annual peak travel speed (km/day) to calculate the approximate time (days) for the movement of peak flows into and out of each area. This information provided guidance around which month to analyze for the remote sensing part of the study.

Remote Sensing Analysis

The remote sensing part of this study aimed to assess whether vegetation differed consistently between low, medium, and high flow years. Presence and absence of vegetation in an area was assessed in three different ways. First, true and false color images of the entire Delta and each of the areas identified for the study were compared visually. Second, change detection for reflectance of red and near IR was performed. Finally, a comparative analysis of NDVI was performed.

Remote sensing data were obtained from the USGS Global Visualization Viewer (GLOVIS) which makes satellite images and sensor data available for the general public (USGS, 2020). For this study, data from the Landsat Thematic Mapping 4 sensor were used. The thematic mapping sensor was carried on the Landsat 4 and Landsat 5 satellites from 1982 until 2012. The resolution of the TM sensor is 30 m per pixel which makes it practical for detecting landscape level information and its 30-year deployment time provides the opportunity to assess seasonal-cyclical and long term changes to landscape patterns. The sensor detects light reflection for seven ranges of the spectrum (Masek, 2020).

Table 1: Spectral detecting by color and wavelength for each band on the LandSat TM

Sensor Band	Color	Wavelength (µm)
1	Visible Blue	0.45 - 0.52
2	Visible Green	0.52 - 0.60
3	Visible Red	0.63 - 0.69
4	NIR	0.76 - 0.90
5	SWIR 1	1.55 - 1.75
6	Thermal	10.40 - 12.50
7	SWIR 2	2.08 - 2.35

All images were processed using Multispec, a multispectral image analysis software program developed by Purdue University and available at no cost to the public (see: https://engineering.purdue.edu/~biehl/MultiSpec/).

Selection of Remote Sensing Data: Remote sensing data used in this analysis were selected based on the results of the hydrology analysis. First, potential years for analysis were identified based on the results of total annual streamflow volume analysis. Years which were identified as having flows in the top third of all years at both Mohembo and Maun Bridge were categorized as high flow years. Similarly, years with flows in the middle and bottom third of all years were categorized as medium and low flow years respectively. Once the potential low, medium, and high flow years were identified, the estimated timing of water delivery to the outer parts of the Delta was used to select the appropriate month of year for image analysis. Links between peak NDVI and peak flooding were not found in literature; however, it was noted that peak NDVI usually lags peak precipitation by 1.5 months (Martiny et al. 2006) with lags anywhere from 0 to 2 months depending on vegetation type (Gaughan et al. 2012). After the potential years and months for analysis were identified, the availability of images was reviewed in

GLOVIS. Based on the availability of images in GLOVIS, two years from each category (high, medium, and low flow years) were selected and used for analysis.

Image Processing: Images covering the majority of the Delta area were selected and zip files for each year were downloaded from the GLOVIS website. The individual band images were combined into single images using MultiSpec. These images formed the basis for all subsequent analyses, including analysis of different areas in the Delta.

Qualitative Visual Assessment of the Full Okavango Delta: Images of the entire Delta for each year were visually assessed using Multispec. First, images were opened in true color and the images were compared between high, medium and low flow years. Next, the same images were opened in false color and the images were compared.

Qualitative and Quantitative Analysis of Areas of the Delta: To conduct a more in-depth evaluation, four areas of the Delta were selected based on the four major distributaries of the Delta. The whole-Delta images for each year were opened, and each area was selected and saved as an individual image. These individual images were still millions of pixels enabling a landscape level analysis. For each of the four areas, each of the six years were assessed visually using true color and false color assessments as described below. Next, two different change detection analyses were run comparing high, medium and low flow years for each of the four areas, according to the scheme below. Each change detection analysis consisted of 12 comparisons for each area resulting in 48 data points for each change detection method (or 96 data points for both methods) when the four areas were taken in aggregate.

Table 2: Comparison of Years in the Change Detection Analysis

Change Detection	Medium Flow 1	Medium Flow 2	Low Flow 1	Low Flow 2
High Flow 1	X	X	X	X
High Flow 2	X	X	X	X
Medium Flow 1			X	X
Medium Flow 2			X	X

The first change detection analysis was a qualitative visual assessment which involved layering two images on top of each other, creating a 14-band image file. The combined image was viewed with areas with higher near-IR reflection in the second image than in the first (plants reflect near IR strongly) to appear green on the image. The combined images were always assembled with the high flow year first, so areas in green would represent more vegetation in the high flow year than the low flow year. Absence of green and abundance of purple would indicate the opposite.

The second change detection analysis was a calculation and comparison of Normalized Difference Vegetative Index (NDVI), which provided quantitative results. For the NDVI analysis, the area 7-band image was transformed algebraically in MultiSpec with the equation (Band 4 – Band 3)/Band 4+Band 3. This transformation resulted in a grayscale single band image, and a calculated NDVI value between -1 and 1. NDVI values close to 0 should indicate a strong predominance of rock and sand (desert) in the area. Low positive values would indicate grass and shrub land. The calculated NDVI values for each image were compared to provide a quantitative assessment of vegetation in the different parts of the Delta under varying flow regimes.

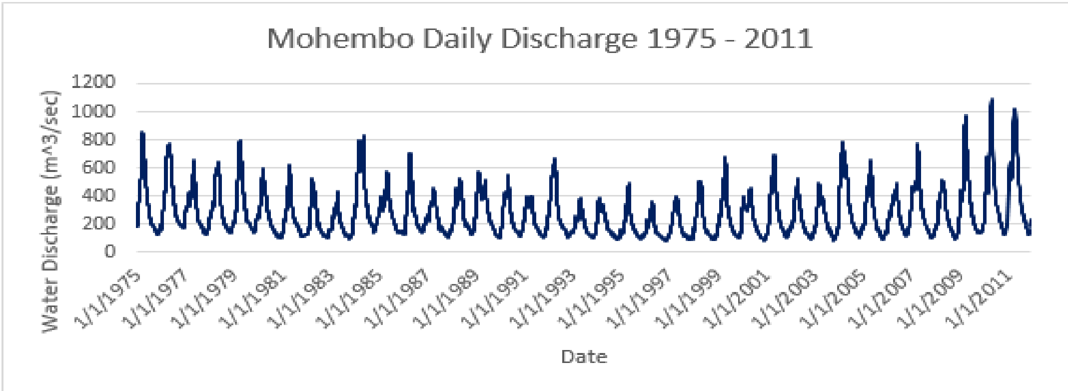
Combined Analysis of Hydrology and Remote Sensing

The inclusion of NDVI in the analysis enabled a quantitative assessment of linkages between vegetation and flow regime. For each of the four areas of the Delta (Selinda, Nqoga-Maunachira, Jao-Boro, and Thaoge) comparisons were run. Minimum, Maximum, and Mean NDVI was compared with total runoff during the three peak months (March, April, May for Mohembo, July, August, September for Maun Bridge), total annual runoff, and monthly runoff for both Mohembo and Maun Bridge. This analysis was performed using a simple scatter plot for each variable. The coefficient of determination (R^2) for each plot was used to characterize correlation.

RESULTS

Hydrology Analysis

Total Annual Streamflow Volume: Substantial variation was observed in daily discharge within each year, across years and between the two sites. Each year, a peak for Mohembo at the entrance to the Okavango Delta can be observed between March and May, and a peak for Maun Bridge at the bottom of the Delta can be observed in July or August. Across years, there are clearly years with higher and lower levels of discharge, with a 58% difference between maximum and minimum peak flows at Mohembo, and a few years with flows at or near to zero at Maun Bridge. There are also major differences in runoff between the top and bottom of the Delta. The bottom of the Delta consistently exhibits substantially lower flows than the top of the Delta, losing a minimum of 94.9% of annual inflow and an average of 98.6%.



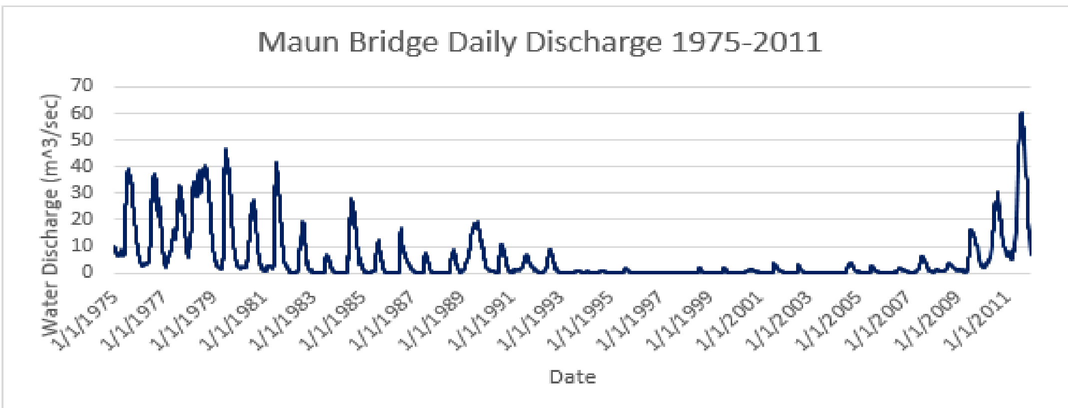


Figure 6. Hydrographs for Mohembo and Maun Bridge

While there are years in which relatively high flows at Mohembo coincide with relatively high flows at Maun Bridge, the flows between the top and bottom of the Delta are not always linked. This is evidenced by a sustained period of low flows at Maun Bridge between 1994 and 2007 for which there is no corresponding pattern of relatively lower flows at Mohembo. When total annual discharge at Mohembo is plotted against total annual discharge at Maun Bridge, there is some correlation (R^2 = 0.40) suggesting that volume of water entering the Delta at Mohembo is partially responsible for the volume of water exiting the Delta at Maun Bridge, but that other factors must also be involved.

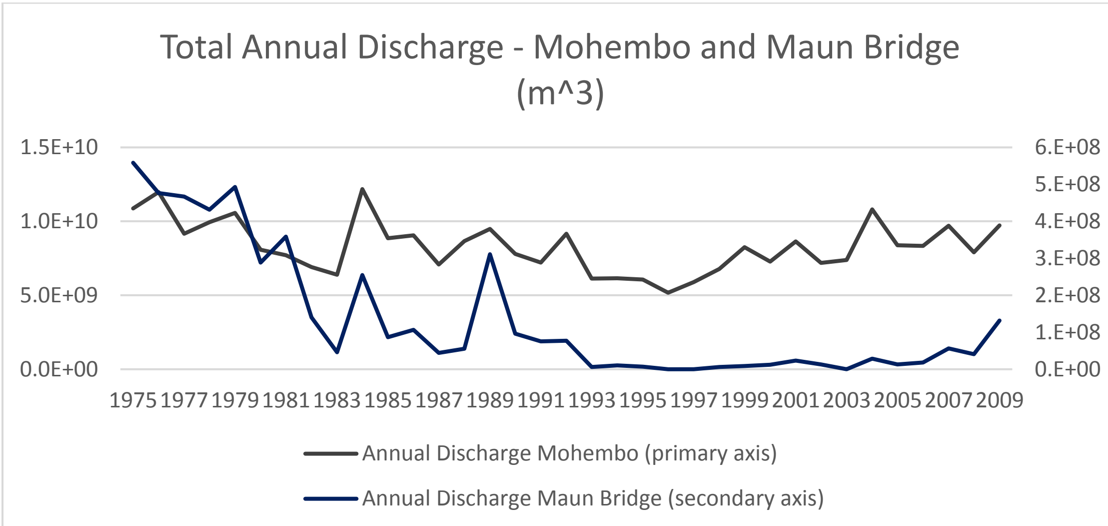


Figure 7: Total annual discharge at Mohembo and Maun Bridge.

In addition to helping with understanding of correlation in flows between Mohembo and Maun Bridge, plotting these flows together assisted with identifying high flow years versus low or medium flow years. A high flow year was defined as a year in which total annual discharge was in the 66th percentile of all annual flows in the study period for both Mohembo and Maun Bridge. There were eight years which met the criteria for high flow years: 1975-78, 1984, 1989 and 2009. Similarly, a medium flow year was defined as a year in which total annual discharge was between the 33rd and 66th percentile of all annual flows in the study period for both gauging stations. There were five years which met the criteria for medium flow years: 1985, 1986, 1988, 1990 and 2008. Low flow years were defined as years where total annual discharge fell below the 33rd percentile for both stations. Seven years met the criteria for low flow years: 1993-1998 and 2000. There was only one year (1982) where total annual flow was in the top third for Maun Bridge and the bottom third for Mohembo, and there were no years where total annual flow was in the top third for Mohembo but lower third for Maun Bridge. This classification of low, medium and high flow years was used to select years for the remote sensing analysis detailed in other sections of this report.

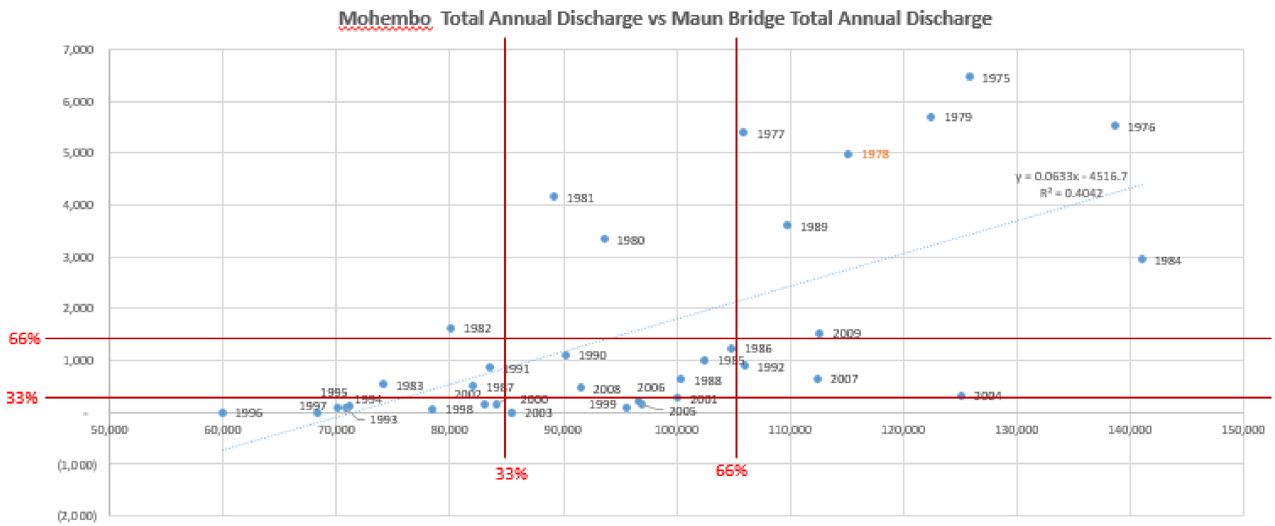
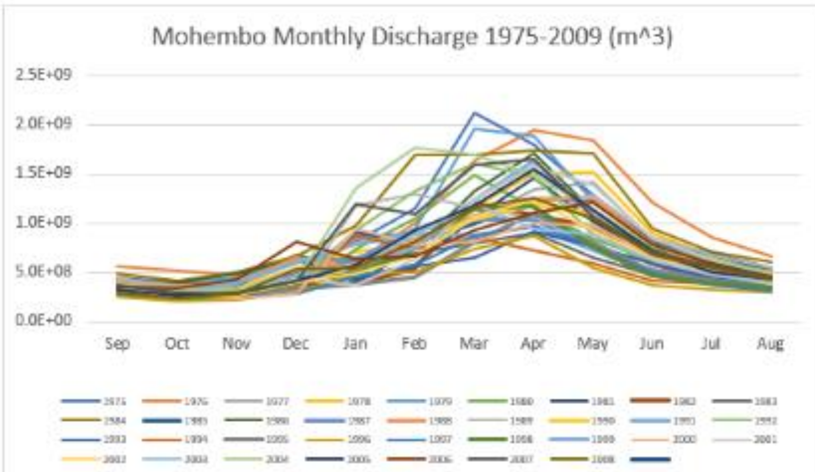


Figure 8: Plotting years according to total annual discharge at Mohembo vs. total annual discharge at Maun demonstrates the correlation (r^2 = 0.4) between flows at the two stations. Adding demarcation lines for the 33rd and 66th percentile of streamflow enables identification of high, medium and low flow years for the remote sensing analysis.

<u>Volume during the Core Runoff Season:</u> Defining a core runoff season required zooming in to look at the streamflow data on a month-by-month basis. Overlaying graphs of monthly flows into the Delta at Mohembo revealed a clear seasonal pattern with peak flows occurring in the early autumn. While a seasonal cycle was clear, there was considerable variation between years in terms of curve shape, with some years having steep ascent to and from peak flow, while others were more gradual. For this reason, a second chart was made illustrating the maximum, minimum, 25th and 75th percentiles and median monthly flows across the period which helped to narrow the core period to between February and May. To further narrow to a three month period, flows during the core runoff period were transformed to flow as a fraction of total annual discharge.



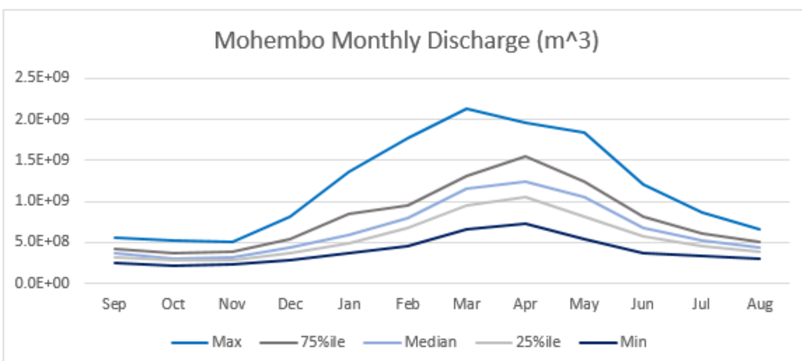


Figure 9: *Top* - Monthly discharge at Mohembo demonstrates a pattern of higher flows during the months of February through June. *Bottom* – Focusing on the median and 25th and 75th percentiles enables a refinement showing peak discharge generally occurring in April.

Plotting monthly discharge as a percent of total annual discharge gave a more consistent view of both the core and non-core runoff seasons, particularly when limited to the maximum, minimum, median and 25th and 75th percentiles. Based on this, the core run off season could be reasonably defined by distinctly elevated flows (visual assessment) with each core month having a minimum of at least 10% of the total annual discharge. For this reason, the months of March, April and May were selected as the core runoff season. Together, these three months contributed 40-45% of total annual discharge on average and exceeded 50% of total discharge in many years.

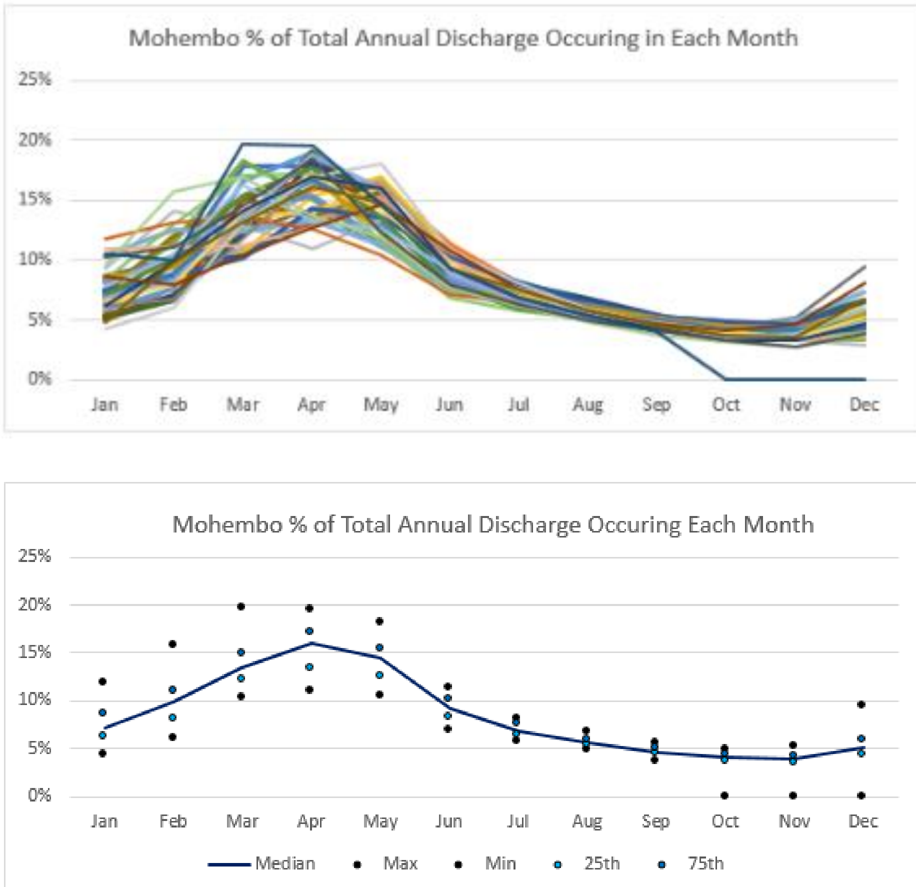
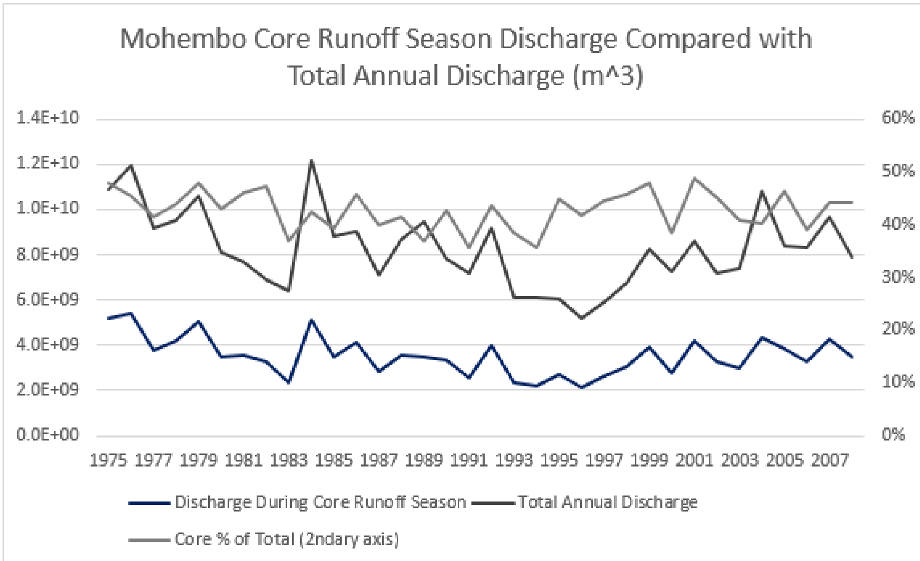


Figure 10: Plotting monthly discharge as a percent of total discharge provided a sharper view of relative total monthly discharge, enabling selection of months included in the core runoff season.

Variation of total annual runoff was largely due to variation in the core runoff season. Plotting discharge during the core runoff season on the same timeline as total annual discharge showed that their patterns of variation between years were nearly identical, with only 2 years when the curve was directionally different between the two. The core runoff season consistently delivered between 40% and 55% of total annual runoff. Core period discharge closely correlated with total annual discharge (R^2=0.88).



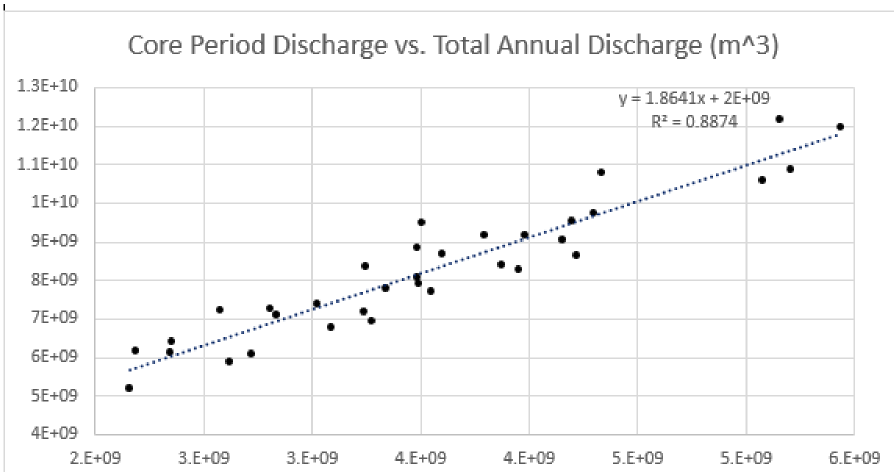


Figure 11: (Top) Time series of annual discharge comparing discharge during core runoff season with total annual discharge. (Bottom): Further illustrating the strong influence core period discharge has on total annual discharge, plotting together shows a strong linear relationship.

Peak Flow Timing and Duration: The majority of peak flows occurred in April and a few occurred in March (figure 12). In addition to understanding when peak flows occurred, it was also useful to quantify how long these high flow levels persist, because that may affect how far down the Delta the water will reach. Peak flows, as defined in the Methods section, lasted from 1-17 days with an average duration of 4.6 days.

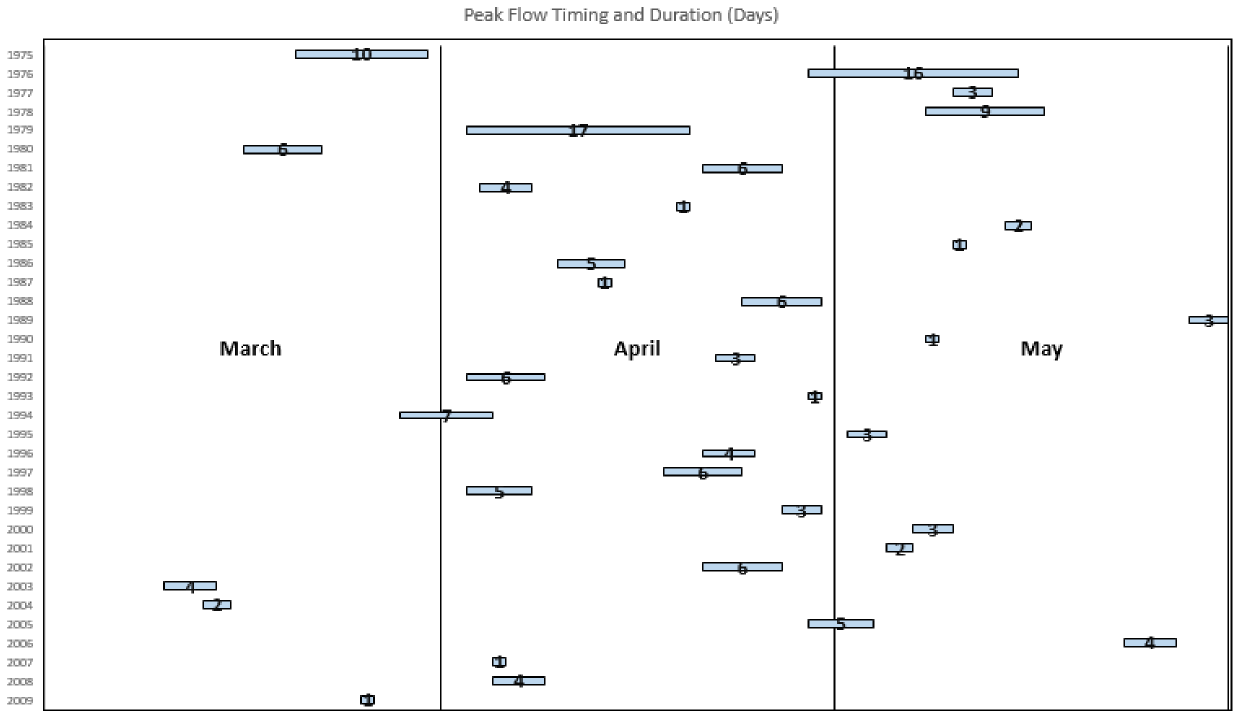
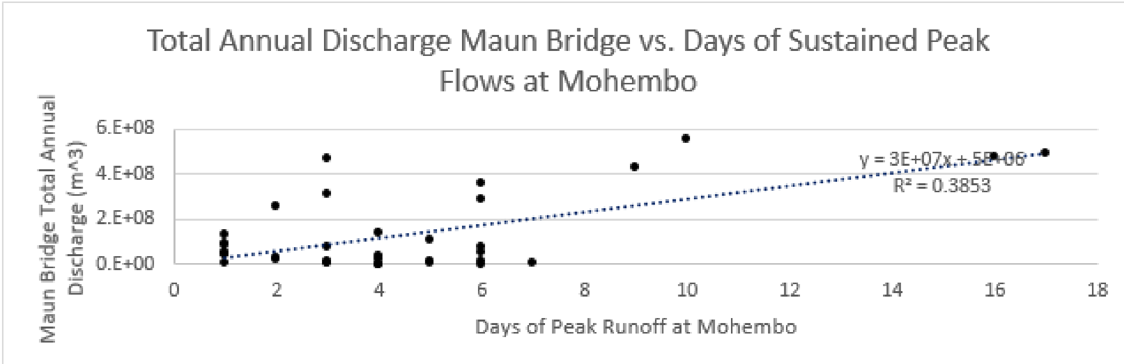


Figure 12: Peak flow timing and duration for each year in the study period at Mohembo

Peak flows seem to have lasted longer in the earlier years of the study period when there were more days of high flow at both Mohembo and Maun Bridge. To test this, total annual discharge at Mohembo and at Maun Bridge was plotted against days of peak flow. The correlation varied, with R^2=0.39 for Maun Bridge and R^2=0.16 for Mohembo. This suggests that total runoff exerts a stronger influence on days of peak flow at Maun Bridge than at Mohembo, which is an interesting but unexpected result.



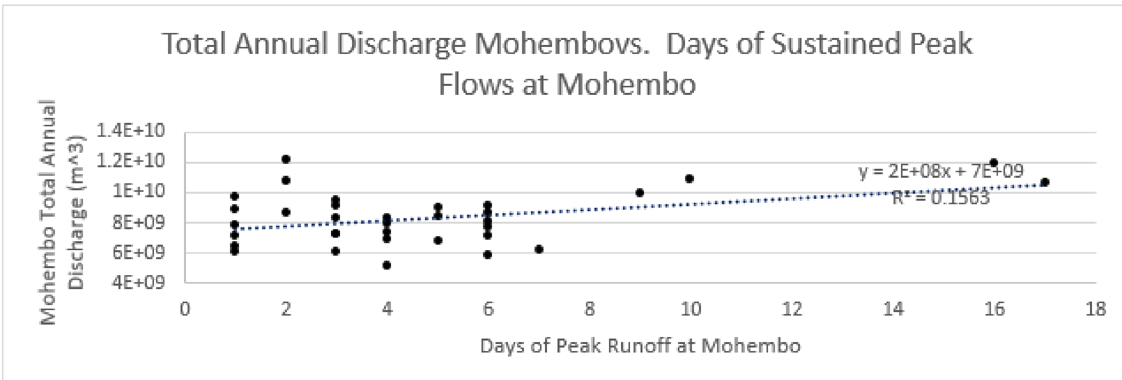


Figure 13: Scatter plots of total annual discharge at Maun Bridge and Mohembo vs. days of peak runoff at Mohembo. Little to no correlation was detected with discharge at Mohembo, however, there does appear to be correlation with discharge at Maun Bridge. The R^2 of 0.39 is larger than expected and suggests that days of peak runoff at Mohembo is at least one factor in runoff volume at Maun Bridge.

Speed of Water Progression through the Delta: Time between peak flows at Mohembo and Maun Bridge was used to estimate speed of peak travel across the Delta. Peak flows at Maun Bridge were observed to occur between July and September, lagging Mohembo by anywhere from 52 to 193 days, with an average of 122 days.

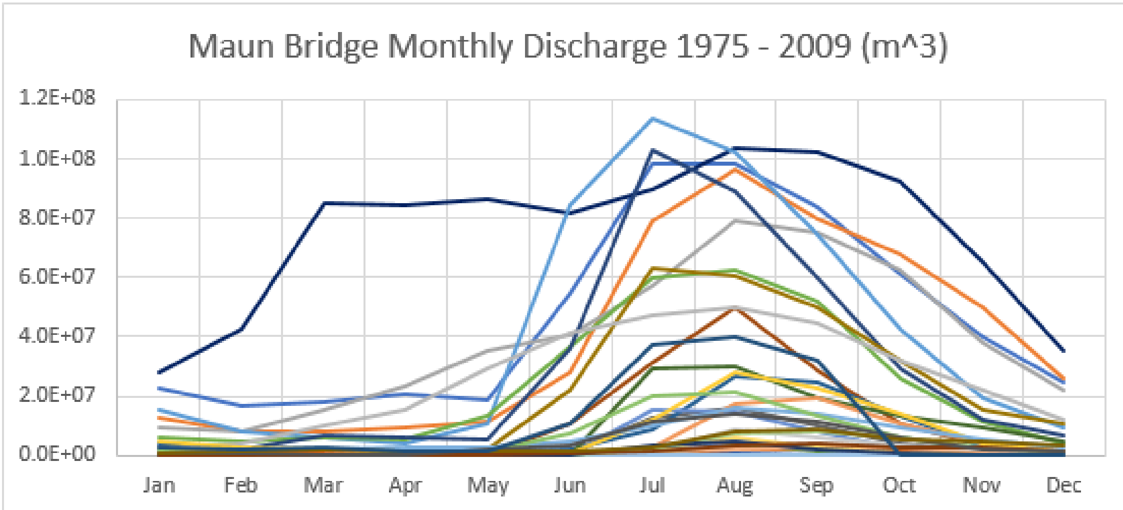


Figure 14: Total monthly discharge at Maun Bridge for all years in the study period. Similar to Mohembo, a clear seasonality is apparent, with peaks generally occurring in July, August or September.

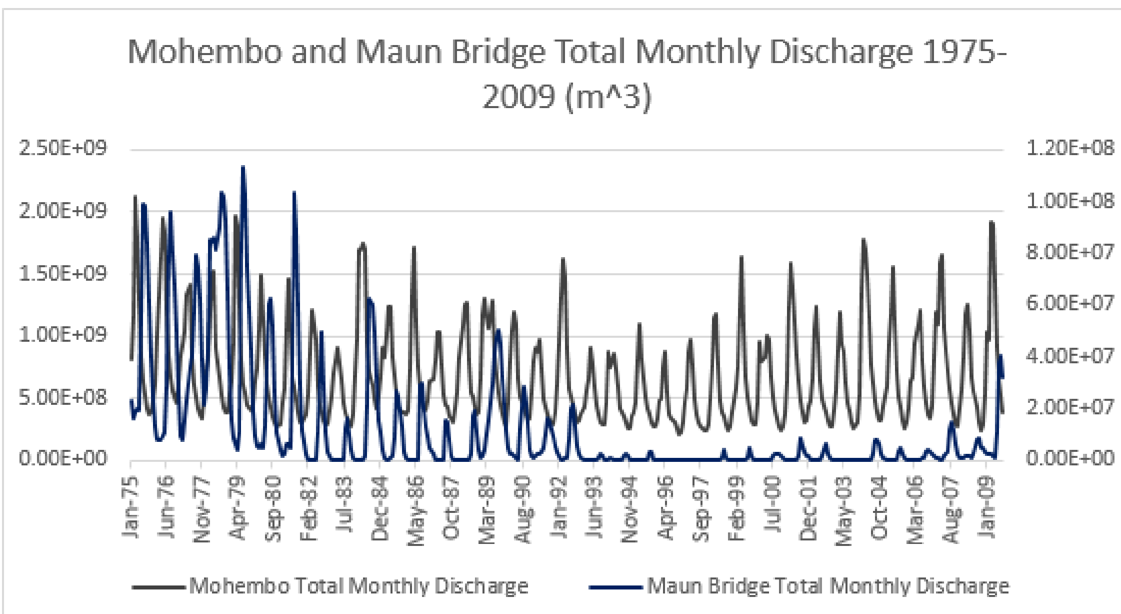


Figure 15: Superimposing monthly discharge from Maun and Mohembo demonstrates a similar seasonal pattern, with Maun Bridge consistently lagging Mohembo

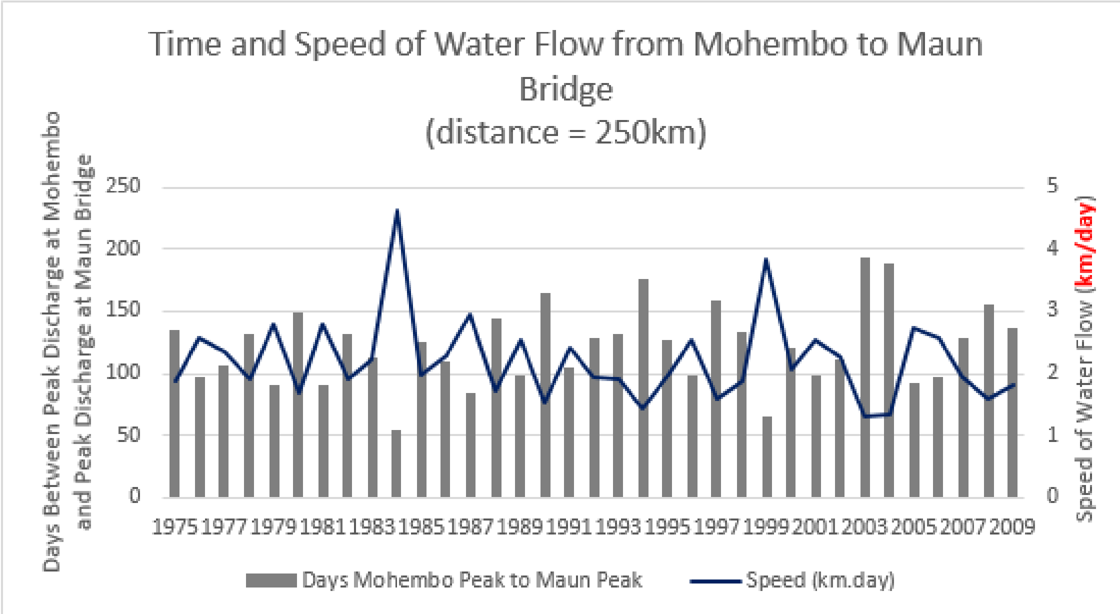


Figure 16: With a few visible outliers, the calculated speed of peak travel between Mohembo and Maun Bridge is generally close to 2km / day, which illustrates the very slow flow characteristic of the areas within the Okavango Delta.

Maun Bridge is 250 km from Mohembo, and the speed at which the hydrograph peak travelled was calculated as between 1.3 and 4.6 km/day and 2 km/day on average. This seemed like a wide range of speed for water flowing over the same ground year after year, so additional analyses were performed to assess drivers behind the differences in timing of peak flows. First, a basic correlation analysis was run to determine if time between peak flows at Mohembo and Maun was related to peak flow volumes at either station. There was little to no correlation found, and it was determined that time between peak flows at Mohembo and Maun is not related to peak flow volumes at either station. Next, time between peak discharges was compared with total annual flow volume at either station. There was little to no correlation ($R^2 < 0.1$ for both), and it was determined that time between peak flows is not related to total annual discharge at either station. The driver(s) of time between peak flows at the top and bottom of the Delta appears to be factors outside the scope of this project.

Pattern of Water Delivery to the Outer Reaches of the Delta: Distances between Mohembo and proximal and distal points of each area of the Delta were determined to range from 105 km – 150 km for proximal points and 150 km – 199 km for distal points. Each area was determined to be between 45 and 50 km from the point of water entering to the end, indicating that the selected areas are each of similar size.

Table 3: Distances from Mohembo to the four study areas of the Okavango Delta

Area Name	**Location**	**Latitudinal Range**	**Longitudinal Range**	**Distance from Mohembo (km)**
Selinda	North East	-18.886148- -18.538143	22.545613 – 23.125631	105 150
Nqoga-Maunachira	South East	-18.960929 - -19.247696	22.765401 – 23.120546	128 177
Jao-Boro	South West	-19.334411 - -19.612809	22.678301 – 23.040364	150 199
Thaoge	West	-19.112173 - -19.554074	22.190140 – 22.573347	112 155

The distance between Mohembo and points in each of the four areas of the Delta was used, along with calculated annual flow rates to estimate the approximate number of days it takes for water to move from Mohembo to other parts of the Okavango Delta.

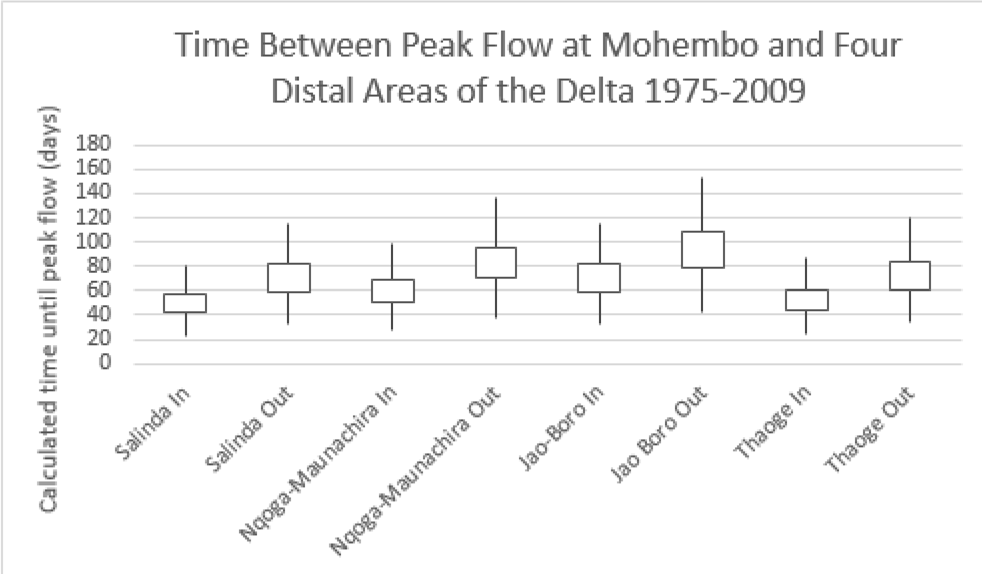


Figure 17: Time for water to travel from Mohembo to each of the four study areas

Finally, the time between peak flows at Mohembo and other parts of the Delta was translated into calculated estimates of peak flow date for each area of the Delta. This information was used to guide decisions about which months to use for the remote sensing analysis.

Table 4: Calculated date of peak flow entering and exiting each study area

Calculated Date of Area Peak Flow										
Year	Mohembo	Salinda In	Salinda Ou	Nqoga-Ma	Nqoga-Ma	Jao-Boro I	Jao Boro Out	Thaoge In	Thaoge	Maun Bridge
1984	14-May	6-Jun	16-Jun	12-Jun	22-Jun	16-Jun	27-Jun	8-Jun	17-Jun	8-Jul
1989	30-May	12-Jul	29-Jul	21-Jul	10-Aug	29-Jul	19-Aug	14-Jul	1-Aug	9-Sep
1990	3-Mar	12-May	12-Jun	27-May	30-Jun	12-Jun	14-Jul	17-May	15-Jun	18-Aug
2008	3-Apr	15-Jun	17-Jul	1-Jul	6-Aug	17-Jul	21-Aug	20-Jun	20-Jul	14-Sep
1994	22-Apr	4-Jun	21-Jun	13-Jun	2-Jul	21-Jun	11-Jul	6-Jun	23-Jun	1-Aug
1996	8-Apr	14-Jun	12-Jul	28-Jun	28-Jul	12-Jul	12-Aug	18-Jun	15-Jul	14-Sep

Remote Sensing Analysis

Selection of Remote Sensing Data: Years for image analysis were selected based on the total annual streamflow analysis, and availability of high-quality images from GLOVIS. Selection of month was based on the analysis of water delivery to the outer parts of the Delta (cross-checked with literature), availability of images, and an approximation of timing for vegetation to grow upon arrival of seasonal flooding based on literature.

Table 5: Dates used for remote sensing analysis

Study Images	High Flow	Medium Flow	Low Flow
Years Selected	1984, 1989	1990, 2008	1994, 1996

Visual Assessment of the Entire Okavango Delta: Visual comparison of Landsat TM images from high-flow, medium-flow and low-flow years provided a clear indication of differences in extent of vegetation, flooding, and of the Delta itself. Conditions in high flow vs. low flow years were clearly distinct across all sections of the Delta. Considerable variation was observed between the two medium flow years selected, however high flow years showed more extensive green vegetation than medium flow years. Medium flow years clearly had a considerably greater areas of vegetation than low flow years.

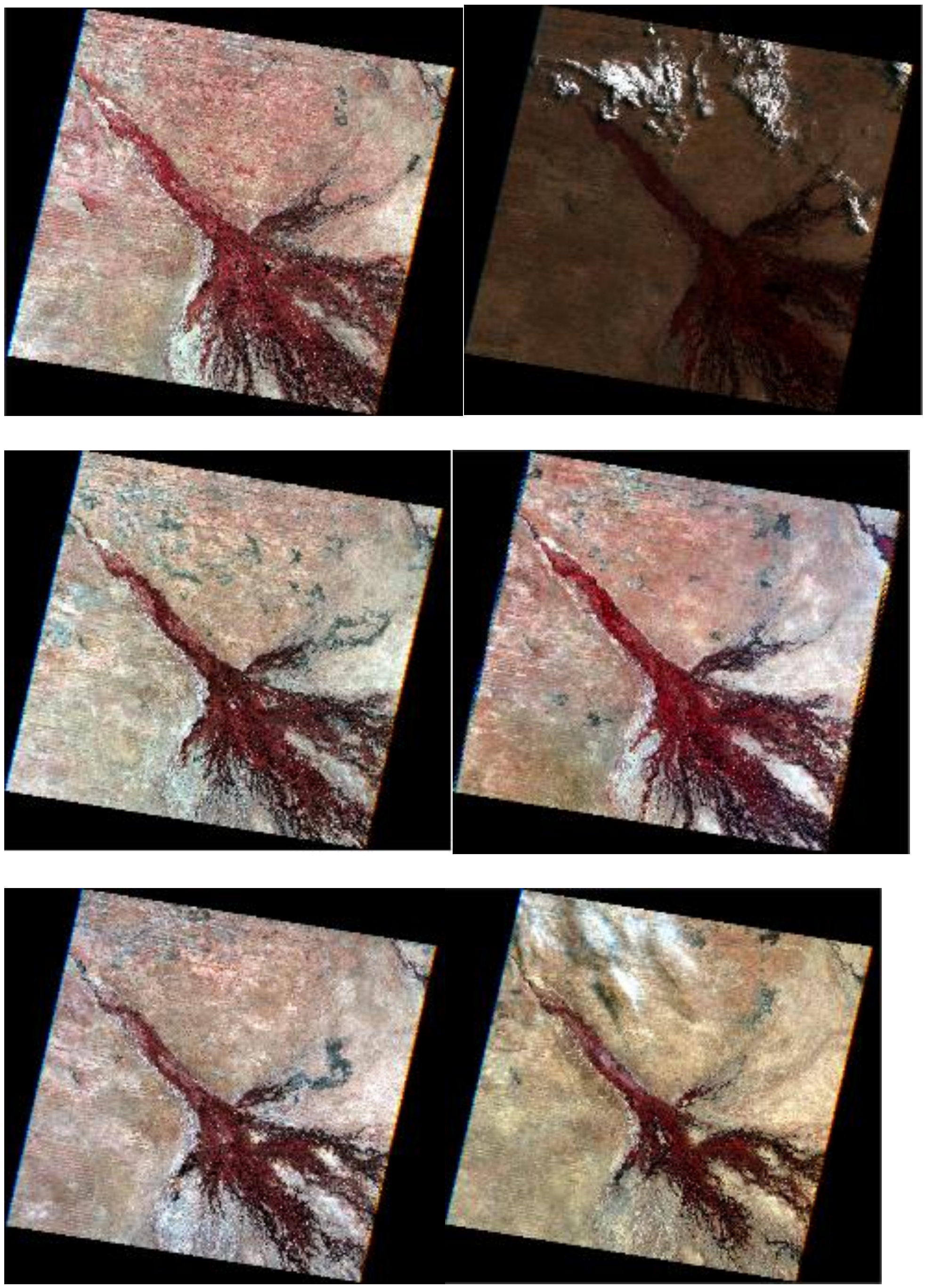
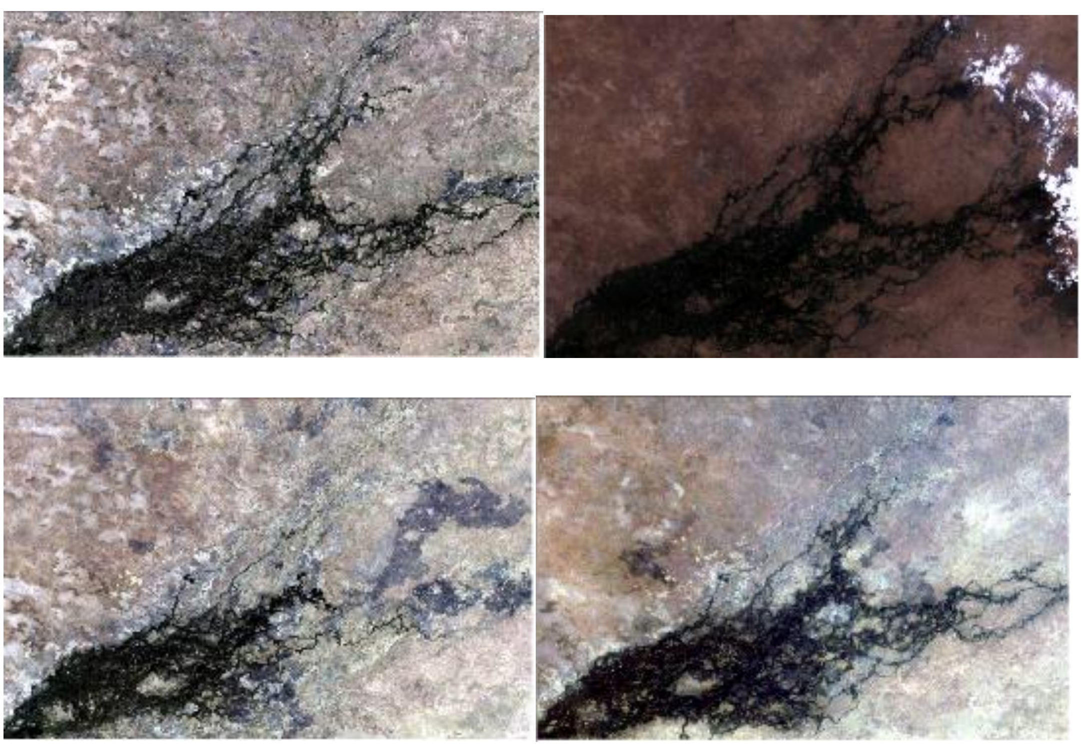


Figure 18: Extent of Delta in two high (top), medium (middle) and low (bottom) flow years.

Visual Analysis of Sub-Area:

Selinda: In the Selinda area of the Okavango Delta, higher flow years consistently showed greater extent of green vegetation than lower flow years. This distinction was apparent both in the extent of the distal reach of vegetation (how far down the Delta green vegetation extended) and in the density of vegetative cover in the more proximal part of the area. Similar distinctions were apparent between medium and low flow years and between high and medium flow years, although the latter was less pronounced. For the Selinda area, these observations were best illustrated by the true color images (below), however; for the other areas the change detection analyses are shown to emphasize differences in near IR reflection.



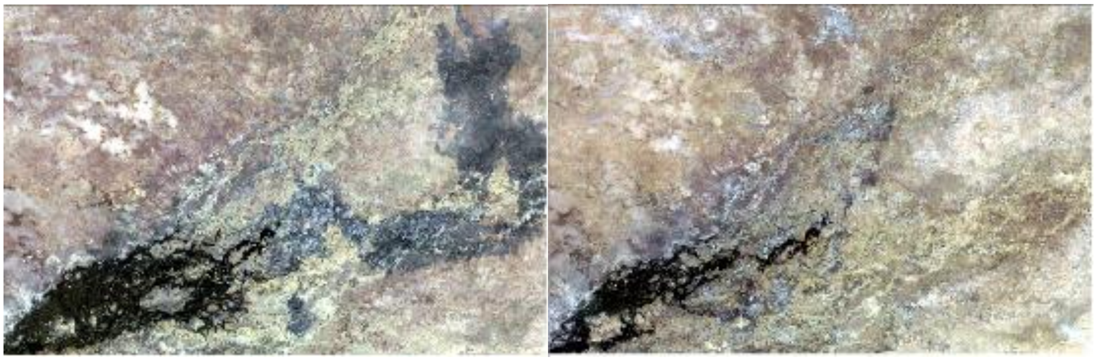


Figure 19: Extent of vegetation in the Selinda Area of the Okavango Delta during high flow (top), medium flow (middle) and low flow (bottom) years

Nqoga-Maunachira: In the Nqoga-Maunachira area, higher flow years generally showed more vegetation than lower flow years; however, one medium flow year (2008) appears to have had more vegetation than one of the high flow years (1984). There was a consistently clear distinction between high flow and low flow years. The distinction was apparent in the density of vegetative cover, but not in the extent of distal reach of vegetation, perhaps because this is a relatively proximal part of the Delta. Similar distinctions were apparent between medium and low flow years. These findings were supported by observation of true and false color images, as well as by the change detection analysis.

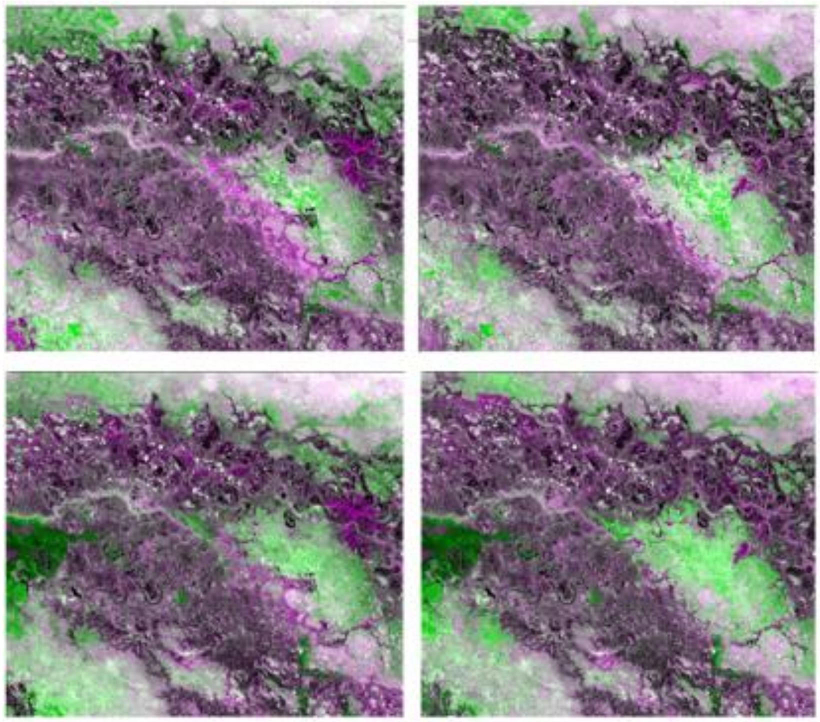


Figure 20: Change detection analysis of Images from high-flow years and low-flow years in the Nqoga-Maunachira area of the Okavango Delta. Abundance of bright green in the images indicates increased near infrared reflection in the higher-flow years, suggesting a greater extent of vegetation.

Jao-Boro: In the Jao-Boro area higher flow years generally showed greater density of vegetation than lower flow years. Low flow years clearly had less vegetation than high or medium flow years, however, the distinction was not clear between high and medium flow years. Owing to the area's density of vegetation and channels, this was more clearly viewed in the change detection analysis (below) than in the true or false color images.

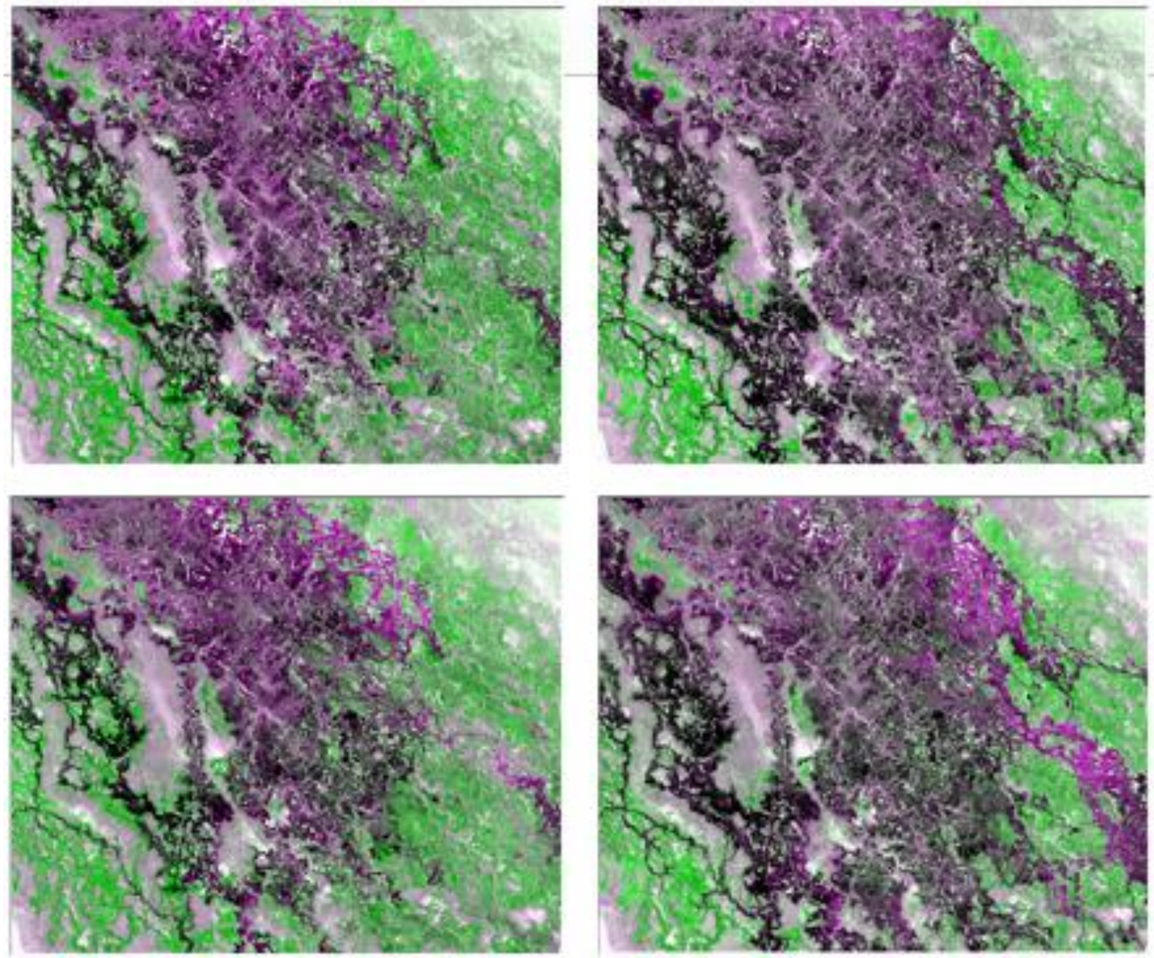


Figure 21: Change detection analysis of images from two high-flow and two low-flow years in the Jao-Boro area of the Okavango Delta. Extensive bright green in the images indicates increased near-infrared reflection in the higher flow years, suggesting that there was a greater amount of vegetation in the high flow years than the low flow years.

Thaoge: In the Thaoge area higher flow years consistently showed greater extent of vegetation than lower flow years. This distinction was apparent both in the extent of distal reach of vegetation and in the density of vegetative cover in the more proximal part of the area. Similar distinctions were apparent between medium and low flow years and between high and medium flow years, although the latter was less pronounced. These findings are supported by observation of true and false color images as well as by the change detection analysis (below).

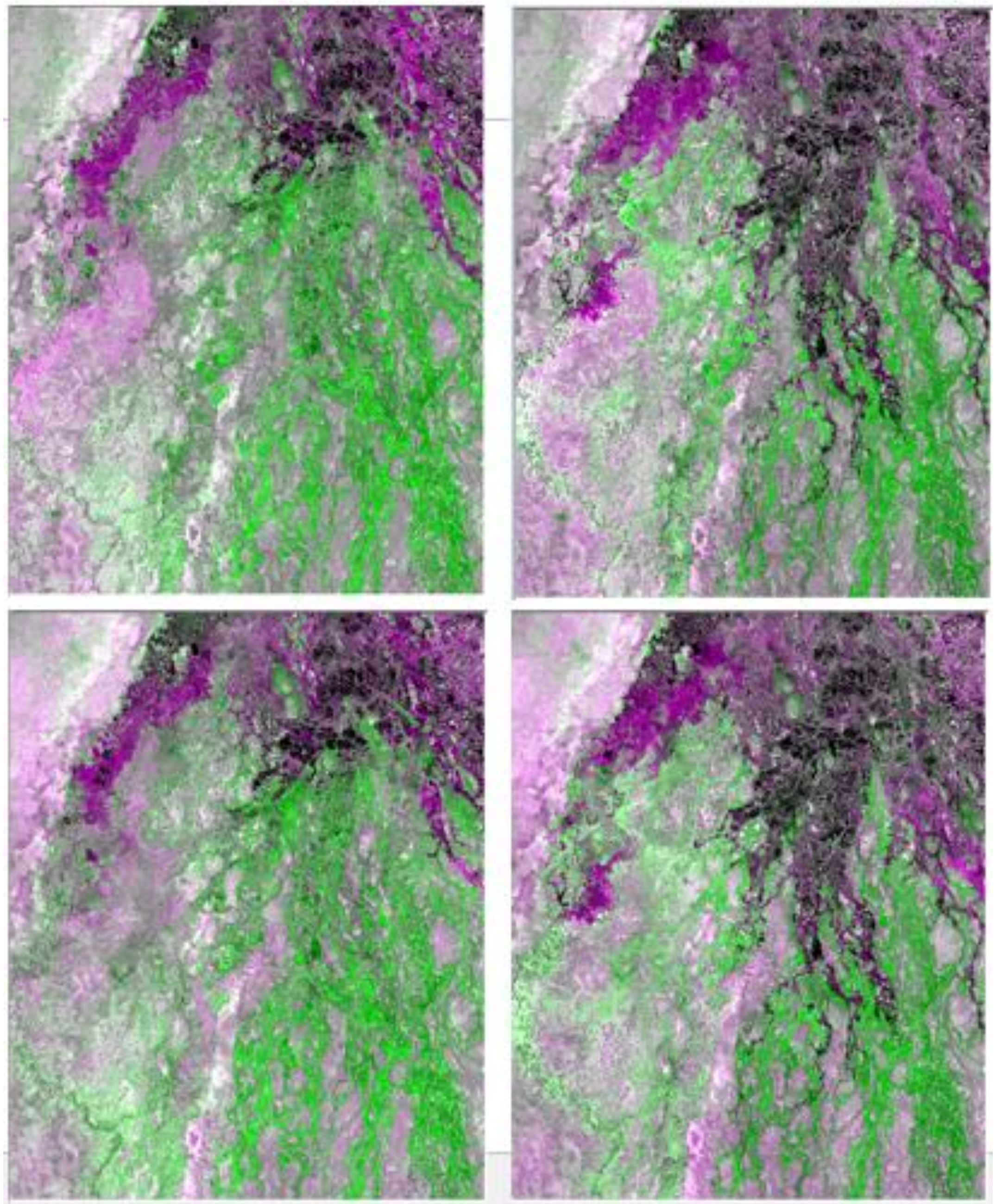


Figure 22: Change detection analysis of images from two high-flow and low-flow years in the Thaoge area of the Okavango Delta. Abundance of bright green in the images indicates increased near infrared reflection in the higher flow year, suggesting that there

was a substantially greater extent of vegetation in the high flow years than the low flow years.

NDVI Analysis

NDVI values in several instances did not support the hypothesis, although visual analysis of the same images did (see limitations in the discussion section). In general, images from high-flow year 1984 and medium flow year 2008 had consistently lower NDVI than was expected. In one instance (Jao-Boro), medium flow year 1990 had a higher than expected NDVI. Aside from this, the NDVI values are within a reasonable range for the physical characteristics of the Okavango Delta. Values close to zero (less than 0.1) generally correspond to barren areas, while values closer to 0.2 correspond to shrub and grassland. Most of the areas observed have a mix of barren desert cover and grasses and shrubs where the seasonal flooding has occurred.

Using the NDVI values generated during the image transformation in MultiSpec, I ran simple subtractive comparisons of NDVI between high-flow, medium-flow and low flow years for each of the Areas of the Delta. Comparisons in which the NDVI in the higher flow year exceeds NDVI in the lower flow year (indicated “higher > lower” in table 6 below) supported my hypothesis. Comparisons in which the NDVI in the higher flow year is less than that of the lower flow year (indicated in red “higher < lower” in table 6 below) did not support my hypothesis.

Table 6: Comparisons of NVDI in 2 images from each high, medium and low flow years. Note: results appearing in red indicate comparisons where the NDVI for a higher flow year was lower than that for a lower flow year.

Selinda NDVI Differences	Low Flow 1	Low Flow 2	Med Flow 1	Med Flow 2
High Flow 1	Higher > Lower	Higher > Lower	Higher > Lower	Higher > Lower
High Flow 2	Higher > Lower	Higher > Lower	Higher < Lower	Higher > Lower
Low Flow 1			Higher > Lower	Higher < Lower
Low Flow 2			Higher > Lower	Higher < Lower

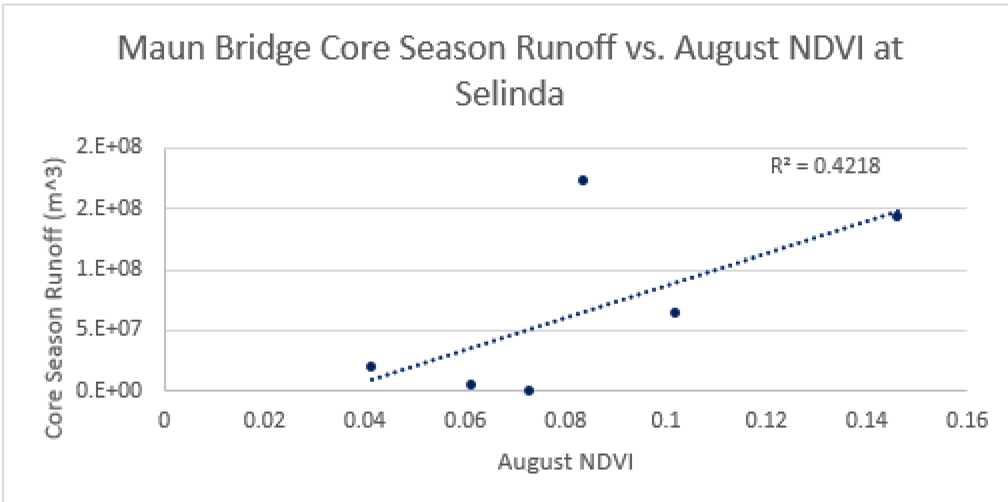
N-M NDVI Differences	Low Flow 1	Low Flow 2	Med Flow 1	Med Flow 2
High Flow 1	Higher > Lower	Higher > Lower	Higher > Lower	Higher > Lower
High Flow 2	Higher < Lower	Higher < Lower	Higher < Lower	Higher > Lower
Low Flow 1			Higher > Lower	Higher < Lower
Low Flow 2			Higher > Lower	Higher < Lower

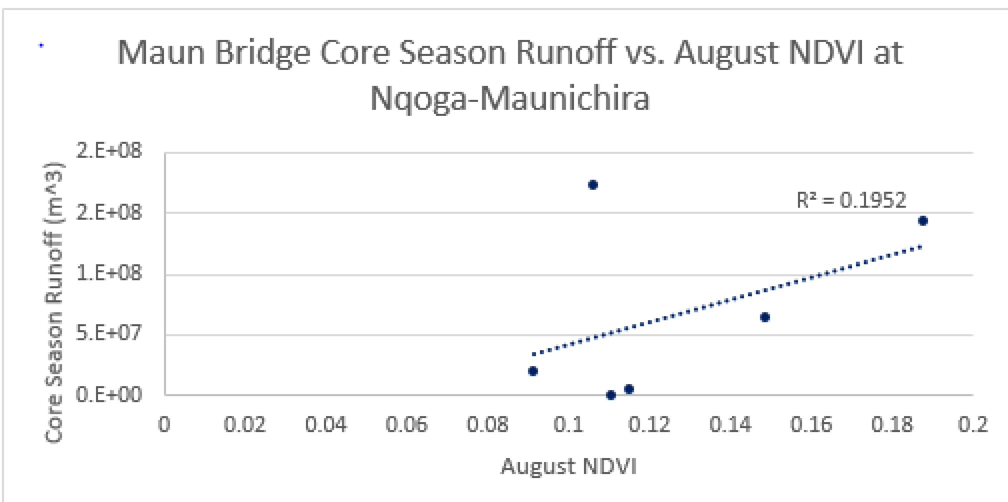
J-B NDVI Differences	Low Flow 1	Low Flow 2	Med Flow 1	Med Flow 2
High Flow 1	Higher > Lower	Higher > Lower	Higher < Lower	Higher > Lower
High Flow 2	Higher > Lower	Higher > Lower	Higher < Lower	Higher > Lower
Low Flow 1			Higher > Lower	Higher < Lower
Low Flow 2			Higher > Lower	Higher < Lower

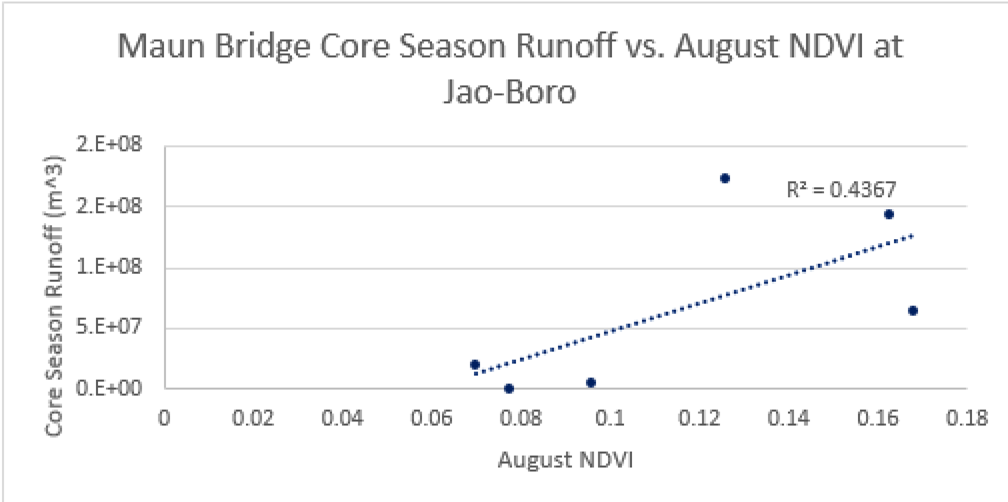
Thaoge NDVI Differences	Low Flow 1	Low Flow 2	Med Flow 1	Med Flow 2
High Flow 1	Higher > Lower	Higher > Lower	Higher > Lower	Higher > Lower
High Flow 2	Higher > Lower	Higher > Lower	Higher < Lower	Higher > Lower
Low Flow 1			Higher > Lower	Higher < Lower
Low Flow 2			Higher > Lower	Higher > Lower

Relationship between NDVI and Stream flow

Mean and maximum NDVI values for each area were correlated with core season runoff with correlations for Maun bridge (R^2=0.22-0.55), depending on area (see Figure 23) being considerably stronger than for Mohembo (R^2=0.00-0.19). For Selinda and Nqoga-Maunachira, no correlation between NDVI and streamflow from Mohembo was observed. For Jao-Boro and Thaoge, a small correlation was observed, however in each case R^2 was less than 0.2. All four areas demonstrated some correlation to streamflow at Maun Bridge, with the mean NDVI being more strongly correlated than the maximum NDVI value in each case.







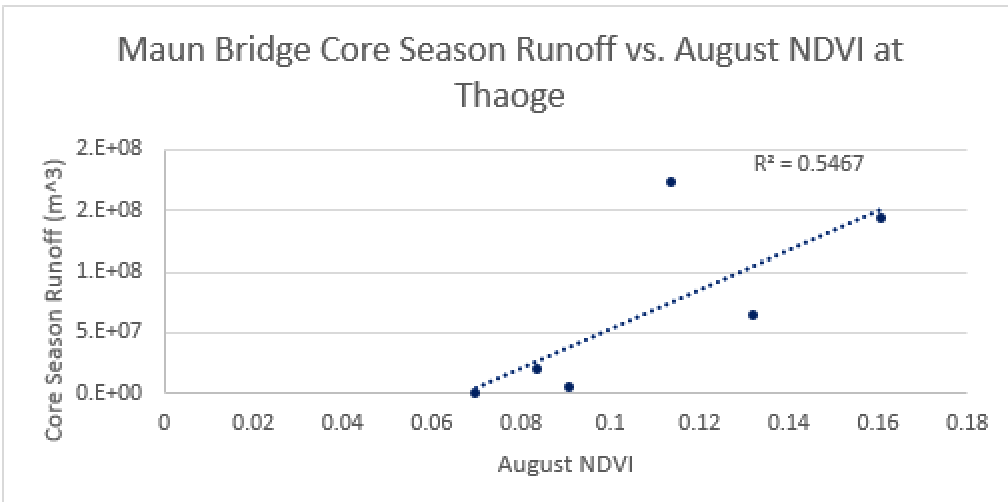


Figure 23: Comparison of August NDVI with core season runoff at Maun Bridge

DISCUSSION

Hydrology

As can be seen from the results, annual streamflow into and out of the Okavango Delta are connected; however, relatively large flows into the Delta do not always equate to relatively large flows out of the Delta, probably due to infiltration and groundwater recharge as water proceeds down the Delta. Local rainfall and previous year inflow volumes can strongly influence groundwater depletion and, as a result, the volume of water stored by groundwater recharge from current year runoff. Groundwater should be included in a more complete analysis. Despite these additional factors, the x-intercept of Figure 8 (6.3 million m^3/year) can be used as an approximation of the minimum flow from Mohembo required for there to be any flow at Maun Bridge. To be more precise, precipitation over the Delta would need to be factored, along with any potential inputs from groundwater or swamps.

Discharge volume during the core runoff season is strongly correlated with total annual discharge confirming that flows during this period are critical to the hydrologic functioning of the ecosystem, which could have implications for future management plans. The duration of peak flows at Mohembo, as quantified in this study, does not seem to be correlated to total discharge at Mohembo, but has some correlation with discharge at Maun Bridge. This suggests that the duration of the highest flows is somewhat independent from the total volume of water entering from Mohembo. Both variables are probably important to the extent of flooding on the Delta and amount of discharge at Maun Bridge.

The speed of peak travel through the Delta is unusually slow for reasons described in the Watershed Description section of this report. It is worth noting that the calculated speed of water flow is highly variable across years, and does not appear to be correlated to the other hydrologic measures evaluated in this study. The only correlation observed was when days between peak flow at Mohembo and peak flow at Maun Bridge was compared with day-of-year of peak flow at Maun Bridge. This really only demonstrates that peak flow at Maun Bridge occurs at a fairly consistent time of year. Because water flows to Maun via surface flow (beyond the Jao-Boro area), additional research would help to shed light on the drivers of *variation* in speed of water movement down the Delta. It could also be insightful to assess in more detail the speed of flow in different parts of the Delta.

The travel time analyses completed for this project provided a simple way to estimate timing of peak flow at different points in the Delta where data availability is limited. This was demonstrated in the estimation of dates of water entering and leaving the four areas of the Delta. This simple approach is clearly limited by the fact that it cannot be validated within the scope of this study. It also ignores several layers of complexity, including variation in flow speed between different parts of the Delta and variation in spatial patterns of groundwater recharge, flooding and evapotranspiration. It is also based on streamflow at two locations at the top and bottom of the Delta. Nevertheless, the results appear reasonable, particularly as timeframes are mathematically constrained to fall between peak discharge at Mohembo and Maun Bridge.

<u>Remote Sensing</u>

The results of the visual analysis with a few noted exceptions support the hypothesis that variation in streamflow influences extent of green vegetation in the Okavango Delta. Visual comparison of images of the full Delta using true color and false color banding during high, medium and low flow years all exhibit more extensive, greener Delta in the higher flow years than the lower flow years. When individual areas were observed in true and false color similar results were observed, especially in the Selinda and Thaoge areas of the Delta. Differences in the Nqoga-Maunachira and Jao-Boro sections were less obvious; however, except for one medium flow year (2008) in Jao Boro appearing to have more vegetation than the high flow years, the results consistently supported the hypothesis. In summary, out of 60 images compared there were 2 observations that do not support the hypothesis. The remaining 58 observations support the hypothesis. This justifies deeper analysis within individual areas.

The visual change detection analysis consisted of 12 composited images in each of the four areas for 48 total comparisons. Of these, two at Nqoga-Maunachira (medium vs. low flow years) and two at Jao-Boro (high vs medium flow years) did not support the hypothesis. The remaining 44 images (92%) supported the hypothesis.

Similar to the visual change detection analysis, the quantitative NDVI analysis compared high vs low vs medium flow years for each area of the Delta, providing a total of 48 comparisons. Of these, 14 (29%) did not support the hypothesis, while 34 (71%)

did. These results for the NDVI analysis are not as strongly supportive of the hypothesis as the visual analysis, but there are advantages and limitations that are worth considering.

Advantages and Limitations of the Remote Sensing Approach Used: For this analysis, the most important advantage that NDVI provides is a quantitative assessment of greenness which can be used to compare with other kinds of metrics. Additionally, NDVI assesses the greenness in the entire image without bias, whereas in the strictly visual analyses, the eye is likely to bias towards the differences in the more distal portions of each area. The disadvantages include potential noise in the signal (e.g. cloud cover can alter the results of an NDVI calculation) and averaging against extremes. These limitations do not prevent a directional evaluation and additional steps can be taken to improve the reliability of the quantitative analysis. The most important step is radiometric normalization of the images. This step can now be automated by using images from Google Earth Engine which has prepared, calibrated time series images.

NDVI and Streamflow

When hypothesizing that NDVI would be related to streamflow in the Okavango Delta, my original thinking was that streamflow *into* the Delta at Mohembo would be found to be related to NDVI in the different areas of the Delta. This was not the case, as very little correlation between NDVI and flows at Mohembo was observed. However, a surprising level of correlation was found between NDVI and flows *out* of the Delta at

Maun Bridge. According to the literature, flow out of the Delta at Maun Bridge is a good indicator of extent of flooding (Milzow et al. 2009) and it seems logical that NDVI would be related to the size of the flood area. Both reflect the overall amount of water in the delta and how far it spreads across the distal portions of the Delta and into the less accessible microsites inside the proximal portions. The fact that mean NDVI values for each area were more closely associated with flow than maximum or minimum NDVI values is not surprising. Minimum values are likely to exist in pixels representing barren sand or salt, and maximum values are probably dependent on micro environmental factors, of which flow may be but a small contributor.

The findings from this study provide insights for water and habitat managers in the Okavango Delta. In particular, the relationships between duration of peak flow, NDVI and discharge out of the Delta at Maun Bridge can help managers prioritize aspects of the natural flow regime during their negotiations with upstream partners. For example, when considering agreements with Namibia and Angola about upstream abstraction of water, care should be taken not to interfere with duration of peak flows into the Delta as well as the total volume of discharge during the core runoff period.

Areas for further research abound, some to address questions that arise out of the results of this study, and some which would increase confidence in the study results. To increase confidence in the study results, it would be beneficial to apply more advanced statistical techniques. It could also be insightful to assess using other sensors for image analysis. To address questions that arose in the course of this study, addition of quantitative rainfall data over the Delta and groundwater recharge would be insightful.

Additionally, it would be interesting to conduct several assessments on a finer spatial scale, particularly assessing the relationship between NDVI and streamflow in the permanent and seasonal swamp areas. It could also prove beneficial to management practices if the analysis was refined to consider different kinds of plants, which could then be extrapolated to specific fauna communities. Finally, whereas this study investigated relationships between flow and NDVI across years, additional insights may be found if a similar study were to investigate relationships across seasons within single years.

CONCLUSION

Extending this study as described above has the potential to add to the existing body of literature by being the first to attempt to explicitly and quantitatively link vegetation to streamflow in the Okavango Delta. This study has shown that: (1) green vegetation is more extensive in the Delta during high flow years than during low flow years, (2) NDVI in sections of the Okavango Delta is related to streamflow *out of* the Delta at Maun Bridge, and (3) NDVI is not related to streamflow *into* the Delta at Mohembo.

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