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Resumen:

RESUMEN

Esta tesina surge después de seis meses de trabajo en el Institute für Wasserwirtschaft, Hydrologie und landwirtschaftlichen Wasserbau (Hannover, Alemania) donde estuve bajo la supervisión de Matthias Beyer. Durante mi estancia trabajé en el proyecto CERPA, dedicado al estudio de la viabilidad de nuevos instrumentos de mercado para valorar la biodiversidad y sus implicaciones socio-culturales, utilizando el ejemplo de los humedales en África subsahariana . En este marco de trabajo se planteó esta tesina.

Los distintos ecosistemas existentes en la naturaleza proporcionan un gran número de bienes y servicios. Muchos de ellos, se encuentran en situación de amenaza debido, entre otras cosas, a las actividades humanas. Existe por tanto una creciente necesidad de desarrollar instrumentos capaces de protegerlos y frenar la destrucción a la que están siendo sometidos. Es comúnmente conocida la designación de áreas protegidas en términos medioambientales, y el concepto de "pago por servicios medioambientales" (PES, por sus siglas en inglés) está siendo implementado en numerosos sistemas de gestión de los recursos naturales. La idea de establecer un valor para estos servicios pretende promover la conservación y el uso sostenible de los espacios naturales mediante distintas técnicas; ofreciendo por ejemplo incentivos a granjeros o propietarios de tierras agrícolas a cambio de un manejo sostenible de sus tierras de cultivo. El proyecto CERPA eligió, como zona piloto los humedales del este de Caprivi (Namibia), debido a su especial localización en la confluencia de dos ríos y sus características hidrológicas y ecológicas.

El objetivo principal del proyecto CERPA es evaluar la viabilidad de mercados internacionales para la obtención de certificados de áreas protegidas, investigando la posibilidad de introducir pagos por los servicios de los ecosistemas. Para lograr este objetivo, es necesario diseñar un plan de manejo de la cuenca del río Zambezi, basado en el conocimiento detallado de los recursos naturales existentes, así como de sus aspectos socio-económicos.

En los capítulos sucesivos de esta tesina, se lleva a cabo, en primer lugar, una localización y caracterización de la subcuenca de Caprivi (Namibia, cuenca del río Zambezi). Se realiza un análisis del río Zambezi utilizando los datos de la estación de aforo de Katima Mulilo, poniendo de manifiesto la variabilidad existente entre el periodo seco y el húmedo en términos de escorrentía superficial.

En segundo lugar, en la llanura de inundación se determinan los mulapos existentes, siendo éstos los cuerpos de agua inundados periódicamente durante la estación húmeda. Para ello se utilizaron técnicas de teledetección y Sistemas de Información Geográfica (GIS).
Se utilizó una imagen satelital (Landsat 5) perteneciente al mes de mayo de 2008, a partir de la cual se calcula su correspondiente índice mndwi (que indica las masas de agua superficial). El mes de mayo fue elegido por coincidir con el final de la estación húmeda (existen dos estaciones bien diferenciadas, estación húmeda de enero a junio, y estación seca de julio a diciembre); las lluvias han terminado y el agua que queda en la llanura de inundación corresponde con las zonas más bajas en las que se encuentran los mulapos. El año 2008 se eligió por ser muy húmedo.

Una vez determinados los mulapos, se calculó el volumen de agua superficial en la llanura de inundación. Ésta fue dividida en 12 sectores, debido a su enorme extensión (en un GIS mediante un "standar watershed delineation" sobre el modelo digital de elevación), y la frecuencia de inundación de cada uno de ellos ha sido evaluada mediante el uso de imágenes satelitales correspondientes al mes de abril de cada uno de los años, entre 2000 y 2011. Esta

información, junto con el volumen de agua calculado, ha sido utilizada para comparar la frecuencia de inundación en cada uno de los polígonos a lo largo de estos años.

Finalmente, se ha calculado el caudal ecológico mínimo del río Zambezi en la estación de aforo de Katima Mulilo por varios métodos. Para ello, el método de Tennant y el cálculo del percentil 90 y 95 han sido elegidos como los métodos estadísticos utilizados para el cálculo del mínimo caudal necesario para la protección de la biodiversidad existente en la zona, así como para garantizar la aparición estacional de los mulapos.

Esta tesina final de Máster pretende ser un primer paso hacia el estudio de los caudales ecológicos en el río Zambezi y la determinación y el estudio de la importancia de los mulapos en la llanura de inundación de la región de Caprivi. Existe poca información y poco estudios hechos en esta concreta zona, y, considerando su elevada importancia ecológica y ambiental, resulta fundamental impulsar y promover estudios que pongan de manifiesto la importancia de su protección, diseñando un plan de gestión adecuado para la cuenca del río Zambezi.

RESUM

Aquesta tesina sorgeix després de sis mesos de treball a l'Institute für Wasserwirtschaft, Hydrologie und landwirtschaftlichen Wasserbau (Hannover, Alemanya) on vaig estar sota la supervisió de Matthias Beyer. Durant la meua estada allí, vaig treballar per al projecte CERPA que tracta sobre l'estudi de la viabilitat de la creació de nous instruments de mercat per a valorar la biodiversitat i les seues implicacions soci-culturals, utilitzant l'exemple dels aiguamolls a Àfrica subsahariana. Sota aquest marc de treball apareix el tema d'aquesta tesina.

Els diferents ecosistemes existents en la naturalesa proporcionen un gran nombre de béns i serveis. Molts d'ells, es troben en situació d'amenaça a causa de, entre altres coses, a les activitats humanes. Existeix per tant una creixent necessitat de desenvolupar instruments capaços de protegir-los i frenar la destrucció a la qual estan sent sotmesos. És comunament coneguda la designació d'àrees protegides en termes mediambientals, i, el concepte de "pagament per serveis mediambientals" (PES, per les seues sigles en anglès) està sent àmpliament implementat entre els sistemes de gestió dels recursos naturals. Es coneix com a "servei dels ecosistemes" a tots els béns proporcionats pels mateixos, que no suposen un benefici econòmic directe. La idea d'establir un valor a aquests serveis pretén promoure la conservació i l'ús sostenible dels espais naturals mitjançant diferents tècniques; oferint per exemple incentius a grangers o propietaris de terres agrícoles a canvi d'un maneig sostenible de les seues terres de cultiu. El projecte CERPA va triar, com a zona pilot els aiguamolls de l'est de Caprivi (Namíbia), a causa de la seua especial localització en la confluència de dos rius i les seues característiques hidrològiques i ecològiques.

L'objectiu principal del projecte CERPA és avaluar la viabilitat de mercats internacionals per a certificats d'àrees protegides, investigant la possibilitat d'introduir pagaments pels serveis dels ecosistemes. Per a aconseguir aquest objectiu, és necessari dissenyar un pla de maneig de la conca del riu Zambezi, basat en el coneixement detallat dels recursos naturals existents, així com dels seus aspectes soci-econòmics.

En els capítols successius que formen aquesta tesina de finalització de Màster, es duu a terme, en primer lloc, una localització i caracterització de la subconca de Caprivi (Namíbia, conca del riu Zambezi). Al mateix temps, es realitza una anàlisi del riu Zambezi utilitzant les dades de l'estació d'aforament de Katima Mulilo, posant de manifest la variabilitat existent entre el període sec i l'humit en termes de vessament superficial.

En segon lloc, es determinen els mulapos existents en la plana d'inundació. Mulapo és el nom local utilitzat per a designar cossos d'aigua inundats periòdicament durant l'estació humida. S'utilitzen tècniques de teledetecció i Sistemes d'Informació Geogràfica (SIG) per a la seua localització.
Per a açò, s'utilitza una imatge satelital (Landsat 5) pertanyent al mes de maig de l'any 2008 a partir de la qual es calcula el seu corresponent índex mndwi. El mes de maig va ser triat per coincidir amb el final de l'estació humida (la zona geogràfica en la qual ens trobem compta

amb dues estacions diferenciades, l'estació humida, de gener a juny, i l'estació seca de juliol a desembre); les pluges han acabat i l'aigua que queda en la plana d'inundació correspon amb les zones més baixes en les quals es troben els mulapos. L'any 2008 s'ha triat per haver sigut molt humit.

Una vegada que els mulapos han sigut determinats, el volum d'aigua que hi ha en la plana d'inundació ha sigut calculat. Al mateix temps, la plana d'inundació ha sigut dividida en 12 sectors, a causa de la seua enorme extensió (aquest procés s'ha realitzat amb ajuda del GIS mitjançant un "standar watershed delineation", amb l'ajuda del DEM), i la freqüència d'inundació de cadascun d'ells ha sigut avaluada mitjançant l'ús d'imatges satelitales corresponents al mes d'abril de cadascun dels anys compresos entre 2000 i 2011. Aquesta informació, juntament amb el volum d'aigua calculat ha sigut utilitzada per a comparar la freqüència d'inundació en cadascun dels polígons al llarg d'aquests anys.

Finalment, s'ha calculat el cabal ecològic del riu Zambezi en l'estació d'aforament de Katima Mulilo. Per a açò, el mètode de Tennant i el càlcul del percentil 90 i 95 han sigut triats com els mètodes estadístics utilitzats per al càlcul del mínim cabal necessari per a la protecció de la biodiversitat existent en la zona, així com per a garantir l'aparició estacional dels mulapos.

Aquesta tesina final de Màster pretén ser un primer pas cap a l'estudi dels cabals ecològics en el riu Zambezi i la determinació i l'estudi de la importància dels mulapos en la plana d'inundació de la regió de Caprivi. Existeix poca informació i pocs estudis fets en aquesta concreta zona, i, considerant la seua elevada importància ecològica i ambiental, resulta fonamental impulsar i promoure estudis que posen de manifest la importància de la seua protecció, dissenyant un pla de gestió adequat per a la conca del riu Zambezi.

RESUME

This Master Thesis arises after six months working on the Institute für Wasserwirtschaft, Hydrologie und landwirtschaftlichen Wasserbau (Hannover, Germany) under the supervision of Dipl.-Hydrol. Matthias Beyer. It is enclosed in the context of the CERPA project which focuses on the evaluation of new market-based instruments for biodiversity conservation and their socio-economic implications, using the example of wetlands in Sub-Sahara Africa .

Ecosystems and biodiversity provide a wide range of goods and services. There is a need for effective instruments to protect them from destruction and deterioration. The designation of areas as 'environmentally protected' is widely used and there exist different kinds of management systems. Among those is the concept of Payment for Ecosystem Services (PES). An ecosystem service is the general name for goods and services provided by ecosystems; benefits which are provided "for free" and do not normally carry a monetary value. The idea of PES is to encourage the conservation and sustainable use of ecosystems, by offering incentives to farmers and landowners in exchange for the responsible management of their land, to ensure the preservation of the ecosystem services. Under this framework the Eastern Caprivi (Namibia) was chosen by the CERPA research team as a pilot area because of its special location and its hydrological and ecological characteristics.

The goal of the CERPA research project is to evaluate the practicability of international markets for protected area certificates, hence to investigate innovative combinations of "protected area approaches" and "Payment for Ecosystem (PES) approaches". To achieve the objective is pursued to establish a management plan based on detail knowledge of the natural resources and the socio-economic aspect.

In this Master Thesis, the characterization of the Caprivi subbasin and its hydrological characteristic are exposed as first step. An analysis of the Zambezi River at Katima Mulilo gauging site was performed, showing its variability during the wet and dry seasons.

Secondly, mulapos (local name for lentic water bodies in the floodplain) were determined by the use of remote sensing techniques and Geographic information System (GIS). For this purpose, a satellite image (Landsat 5) of May 2008 was used and its mndwi index (for superficial water bodies) mapped. The month of May was chosen because it corresponds to the end of the wet season; rains have stopped and the remaining water indicates the lower areas where the mulapos are. The year 2008 was chosen because it was a very wet year.

Once the mulapos were determined, the water volume that remains in the floodplain was calculated. Besides, the floodplain was divided into 12 sectors, due to its huge extension, and the frequencies of flooding in each of them were determined by the use of satellites images for the month of April each year, from 2000 to 2011. This information, together with the volume calculated, was used to compare the occurrence of flooding in the different polygons over time.
Finally, different methods were used to calculate the environmental flow in the Zambezi River at the Katima Mulilo gauging station. The Tennant Method and the Percentile 90 and 95 are the statistical methods chosen to establish a minimum flow to protect biodiversity and encourage the permanence of the mulapos in the floodplain.

The literature about these topics in the Zambezi River Basin is very limited; a deeper study about its flow requirements and the characterization of the mulapos as characteristic features in the floodplain would be of great interest to preserve its biodiversity. This Master Thesis is intended to be as a first step concerning with future research in order to design a complete management plan of the river basin.

Palabras clave:
ENVIRONMNETAL SCIENCE, ENVIRONMENTAL FLOW, HYDROLOGY, GIS, REMOTE SENSING, ECOSYSTEM SERVICES.

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Index

1 Introduction and background ... 1
1.1 The importance of the wetlands and floodplains. The flood pulse concept. ... 3
1.2 Distinctive features in the floodplain: Mulapos and Kasayas. Ecological importance ... 7
1.3 Environmental flows ... 10
2 Objectives ... 13
3 Study area. ... 15
3.1 Zambezi River Basin. Caprivi Region. ... 15
3.2 Physical environment. Topography, geology and land use ... 21
3.2.1 Subbasin scale ... 21
3.2.2 Regional scale ... 22
3.2.3 Local scale ... 25
3.3 Main characteristics of the Mulapos and Kasayas ... 26
3.4 Hydrology and meteorology ... 27
3.4.1 Rainfall ... 27
3.4.2 Runoff ... 28
3.4.3 Air temperature ... 32
3.4.4 The potential evapotranspiration ... 33
3.4.5. The hydrological system ... 34
3.5 Ecological characteristic and biodiversity of the floodplain ... 36
3.6 Livelihood and socio-economic aspect ... 38
3.7 Threats in the Caprivi subbasin ... 42
4 Methods ... 45
4.1 Hydrological characterization of the river flow pattern ... 45
4.2 Determination of the Mulapos using remote sensing ... 47
4.3 Calculation of the water volume of the floodplain ... 51
4.4 Assessment of Environmental Flow in the Caprivi Region. ... 52
4.4.1 Tennant Method ... 55
4.4.2 Percentile 90, 95 (Q347 and Q330) ... 57
4.4.3 Range of Variability Approach (RVA). ... 58
5 Results and discussions ... 63
5.1 Hydrological characterization of the river flow ... 63
5.2 Determination of the mulapos using remote sensing techniques ... 72
5.2.1 Comparative assessment of the different flooding during the years 2000-2011. ... 73
5.2.2 Maps with the flooding for each of the years studied ... 79
5.3 Assessment of the environmental flow. ... 87
5.3.1 Tennant Method ... 87
5.3.2 Environmental flows with Percentile 90 and 95 ... 90
5.3.3 Range of Variability Approach and Hydrological Alteration ... 96
5.3.4 Comparative assessment of environmental flow regimes. ... 104
6 Conclusions ... 107

7 Further research ... 111
8 References ... 113
9 Annex 1. Tables ... 121
10 Annex 2. Maps. ... 129

Acronyms

PES	Payment for Ecosystem Services
GIS	Geographic Information System
CERPA	Research Project for Certification of Protected Areas
NNF	Namibia Nature Foundation
MEA	Millennium Ecosystem assessment
EC	Ecosystem Services
SADC	Southern African Development Community
CRU	University of east Anglia Climatic Research Unit
FAO	Food and Agricultural Organization of the United Nations
DAW	Department of Water Affairs
HQ	Highest Flow
LQ	Lowest Flow
MQ	Mean Flow
PET	Potencial Evapotranspiration
P	Precipitation
T	Temperature
NDWI	Normalized Difference Water Index
NDVI	Normalized Difference Vegetation Index
MNDWI	Modified Normalized Difference Water Index
DEM	Digital Elevation Model
USGS	United States Geological Survey
NIR	Near Infrared
MIR	Middle Infrared
TM	Thematic Mapper

1 Introduction and background

The ecosystems of our planet are severely threatened by human activities. Climatic change, loss of biodiversity, deforestation and wetland destruction are some of the main global environmental issues. A quick response is required to avoid their further deterioration and to safeguard their ecological value.

Ecosystems and biodiversity provide a wide range of goods and services. There is a need for effective instruments to protect them from destruction and deterioration. The designation of areas as 'environmentally protected' is widely used and there exist different kinds of management systems. Among those is the concept of Payment for Ecosystem services (PES). An ecosystem service is the general name for goods and services provided by ecosystems; benefits which are provided "for free" and do not normally carry a monetary value. The idea of Payment for Ecosystems Services is to encourage the conservation and sustainable use of ecosystems, by offering incentives to farmers and landowners in exchanged for the responsible management of their land to ensure the preservation of the ecosystem services present.

In this context the research project CERPA (**C**ertification of **P**rotected **A**reas) was set up. The project focuses on the evaluation of new market-based instruments for biodiversity conservation and their socio-economic implications, using the example of wetlands in Sub-Sahara Africa. The research is a cooperation between Hannover University (Germany) and the Namibia Nature Foundation (NNF).

The Eastern Caprivi was chosen by the CERPA research team as a pilot study area because of its location on the confluence of the rivers Zambezi, Kwando, Linyanty and Chobe and its hydrological and ecological characteristics. This Wetland Area provides many ecosystem services that are internationally important (such as tourism, birdwatching, wildlife) and therefore the conservation and protection of these ecosystem service are of great importance, to ensure the enjoyment of these "Ecosystem Services" in the future.

The focus of the research project is on detailed knowledge of the natural resources, as well as the socio economics aspects, in order to establish a management plan that encourages development and protection. Worldwide biodiversity is decreasing and people who live in wetlands and floodplains often do not know how valuable their environment is and how the damage to the natural resources will diminish their long-term livelihoods.

The Millennium Ecosystem Assessment (MEA, a four year international work program launched by United Nations Secretary-General Kofi Annan in June 2001. Primary report: 2005) established a framework for communicating the key role of ecosystem services for human-well being to decision market and to the private business. Also the concept of Payments for Ecosystem Services (PES) gains more public recognition as an efficient market-based instrument for nature conservation and rural development.

Under this framework this thesis arose, after six months working in the *Institute für Wasserwirtschaft, Hydrologie und landwirtschaftlichen Wasserbau* (University of Hannover) as an internship through the Erasmus Practices agreement. During that period I have been involved in the project CERPA and have worked on that topic drawing up the present document. It is mainly focused on the study of the importance of the environmental flows in the Zambezi River (Namibia) and its associated floodplain. The hydrological behavior of the study area and its special water bodies are also explain.

Therefore, an analysis about the river and its floodplain has been carried out in a place where there is no standard methodology developed and where the available data and previous studies are relatively scarce. Similarly, a comprehensive approach about the effect of the flow regulation in rivers and floodplain is given, considering both as a structural unit which should be managed as a whole.

For this project, data from different sources was selected. All the studies carried out by the CERPA team were fundamental to characterize the study area as well as the historical data of the Zambezi River Basin in order to study the hydrological behavior. Also, satellite images (Landsat-7) were essential to determinate the features of the area, define mulapos and the other water bodies and study the different flooding in the different years in which data is available. Different software was used like GIS with various purposes, and the IHA, specific for the calculation of environmental flows.

1.1 The importance of the wetlands and floodplains. The flood pulse concept.

Wetlands may be defined as those areas where an excess of water is the dominant factor determining the nature of soil development and the types of animals and plant communities living at the soil surface. They occur at the edge of aquatic or terrestrial systems. These areas include riverine floodplains, papyrus swamps, marshes, mangrove swamps and estuaries. By definition would be significantly altered by a change in their flow and/or inundation regime, with a frequency and duration sufficient to support a prevalence of vegetation typically adapted for life in saturated soil conditions (The World bank (2010). The Zambezi River Basin. A Multi-Sector Investment Opportunities Analysis. Volume III. State of the Basin. June 2010. *The World Bank. Water Resources management Africa Region*). Their importance derives from biodiversity, socio economics values and physical and/or hydrological significance.

The MEA defines Ecosystem Services as “the benefits people obtain from ecosystems. These include provisioning services such as regulation of floods, drought, land degradation and disease; supporting services such as soil formation and nutrient cycling; and cultural services such as recreational, spiritual, religious and other nonmaterial benefits”.

Wetlands provide a wide range of goods and services of local, national and international importance. For local people, they provide benefits such as drinking water and water for livestock, floodplain for agriculture and pasture for grazing in the dry period, fisheries as a protein source, plant material for house construction, etc. In the same way they support wildlife, are essential for biodiversity conservation and also play a crucial role in maintaining water quality and regulating river flows. Wetlands absorb and attenuate flows from upstream catchment areas, releasing this “trapped” water slowly over a period of several months and maintaining flows during the dry months (Mott MacDonald, 2007).

In general terms, ecosystem services could be grouped into 4 main classes (source: Millennium Ecosystem Assessment. (2005). Ecosystems and Human Well-Being: Wetlands and Water Synthesis. *World resources Institute, Washington, DC*).

1. Provisioning services

This could be considering as one of the most important ecosystem services. Wetlands are the principal supply of food (fish, wild game, fruits and grains), fresh water (domestic, industrial and agricultural use), fiber and fuel, biochemical (extraction of medicines and other materials from biota) and genetic material (genes for resistance to plant pathogens, ornamental species, etc.). Should be noted that, in developing countries, inland fisheries are particularly important as they are sometimes the most primary source of animal protein to which rural community have access.

2. Regulating services

One of the most important roles of wetlands may be the regulation of global climate change through sequestering and releasing a major portion of fixed carbon in the biosphere. They also have influence in the local and regional temperature, in the precipitation patterns and in other climatic process. Wetlands are also useful for water purification and detoxification of waste; some of them have been found to reduce the concentration of nitrate by more than 80%, because of that they are sometimes used as green filters.

Wetlands provide a wide array of hydrological services, regulating and mitigating the river flows and promoting the groundwater recharge. Floods are natural phenomenon very important for the maintenance of the wetlands, as they depend basically on it. In the same way, wetlands pay an important role diminishing the negative effects of big flooding, mitigating its potential impact to the nearby population.

Likewise, they help to regulate the soil erosion and provide habitat for pollinators.

3. Cultural services

Wetlands provide significant aesthetic, educational, cultural and spiritual benefits and inspiration. It is also important for ecotourism.

4. Supporting

Wetlands support a high biodiversity and are important for the nutrient cycle.

In the figure 1 below, the main ecosystem services related to wetlands are shown.

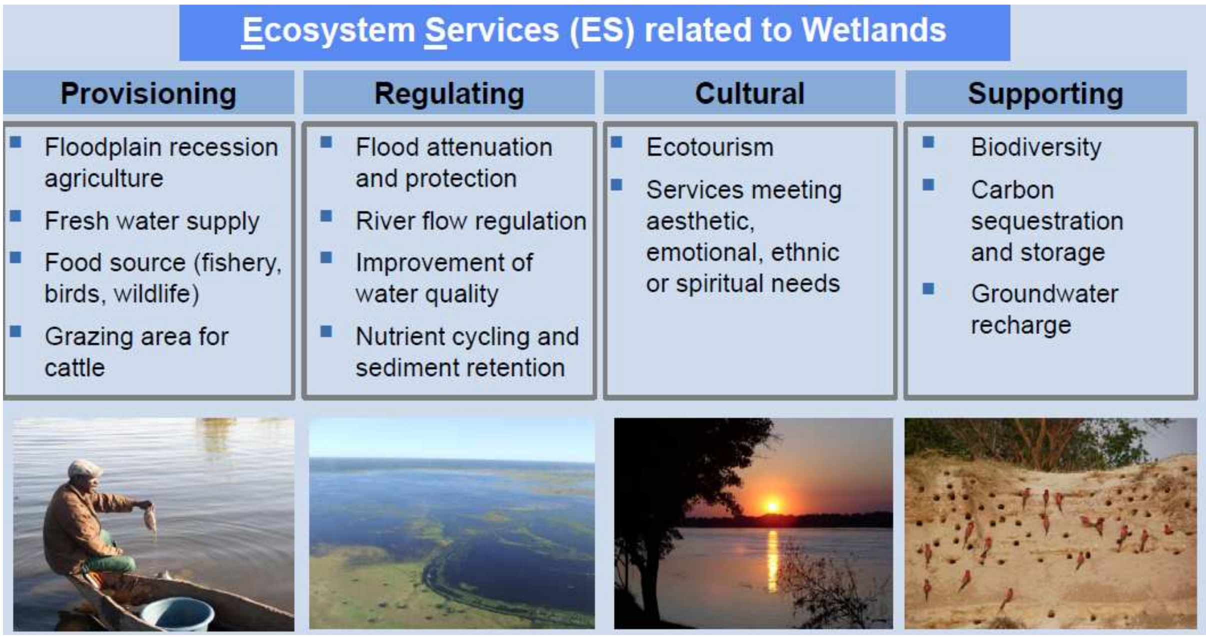

Figure 1: Ecosystem services related to Wetlands.
Source: Matthias Beyer. Redraw after Millennium Ecosystem Assessment. Ecosystem and human well-being: wetlands and water. 2005

The wetlands in Eastern Caprivi are flooded annually due to the rise of the water level in the Zambezi River. The **flood pulse concept** is a hypothesis that describes an ecological response to flood pulse hydrology (Junk et al., 1989). The flood pulse concept was firstly developed to describe seasonal changes in water levels on Amazonian floodplains and their relationships to functional dynamic and the maintenance of species diversity (Junk 1982, 1997; Junk and Howard-Williams, 1984; Junk et al., 1989; National Research Council, 1992; Bayley, 1995). The interconnection of the river channel and floodplain is critical because functions such as production, decomposition, and consumption are driven by the flood pulse (Grubaugh and Anderson, 1988; Sparks et al., 1990) and water fluctuation drives successions (van der Valk, 1981; Finlayson et al., 1989; Niering, 1994; Middleton, 1999a).

The flood pulse is the principal driving force responsible for the existence, productivity and interactions of the major biota in river-floodplain system. We can define floodplain as “areas that are periodically inundated by the lateral overflow of rivers or lakes, and/or by direct precipitation or groundwater; the resulting physicochemical environment causes the biota to respond by morphological, anatomical, physiological, phonological and/or ethological adaptations, and produce characteristic community structures” (Junk et al., 1989). This is an ecological definition which means that the flooding causes a perceptible impact of biota and that biota display a defined reaction to flooding.

From a hydrological aspect, floodplains are part of the drainage system of rivers and are periodically affected by transport of water and dissolved and particulate material. From an ecological point of view, they represent transition zones between aquatic and terrestrial states and they links river channels with permanent lentic bodies and permanent dry lands.

The river and its floodplain should be considered as one unit with regards to the water, sediments and organic budgets (river-floodplain system). This system provides important habitats for the biota which is used for lives cycle related to the flood pulse in terms of its annual timing, duration and the rate of rise and fall.

The flood pulse is the driving force for river-floodplain systems and maintains them in a dynamic equilibrium. A regular pulse allows organism to develop adaptations and strategies for efficient utilization of habitats and resources within the aquatic/terrestrial transition zone, rather than depend solely on permanent water bodies or permanent terrestrial habitat.

Therefore, it is considered necessary establish a minimum environmental flow in the Zambezi River in order to guarantee the maintenance of the floods, wetlands and variety of dry lines that occurs in the Eastern Caprivi. The following chapter will define the concept of environmental flow whilst in following chapters, some methods for the assessment are described. Likewise, mulapos are defined and determined as important features which should be considered to ensure the ecological diversity of the study area.

1.2 Distinctive features in the floodplain: Mulapos and Kasayas. Ecological importance

Within the study area four main types of aquatic ecosystems were recognized: perennial rivers, mulapos, lakes and pans.

The water forms a variety of dryland and wetland habitats that varies during the year, being exploited in different ways and with different methods. Because the amount of such habitats and the way they change (the difference between dry and wet seasons is huge), it turns out complicated to establish a clear classification of them. The figure 2 below shows some of the main aquatic habitats available.

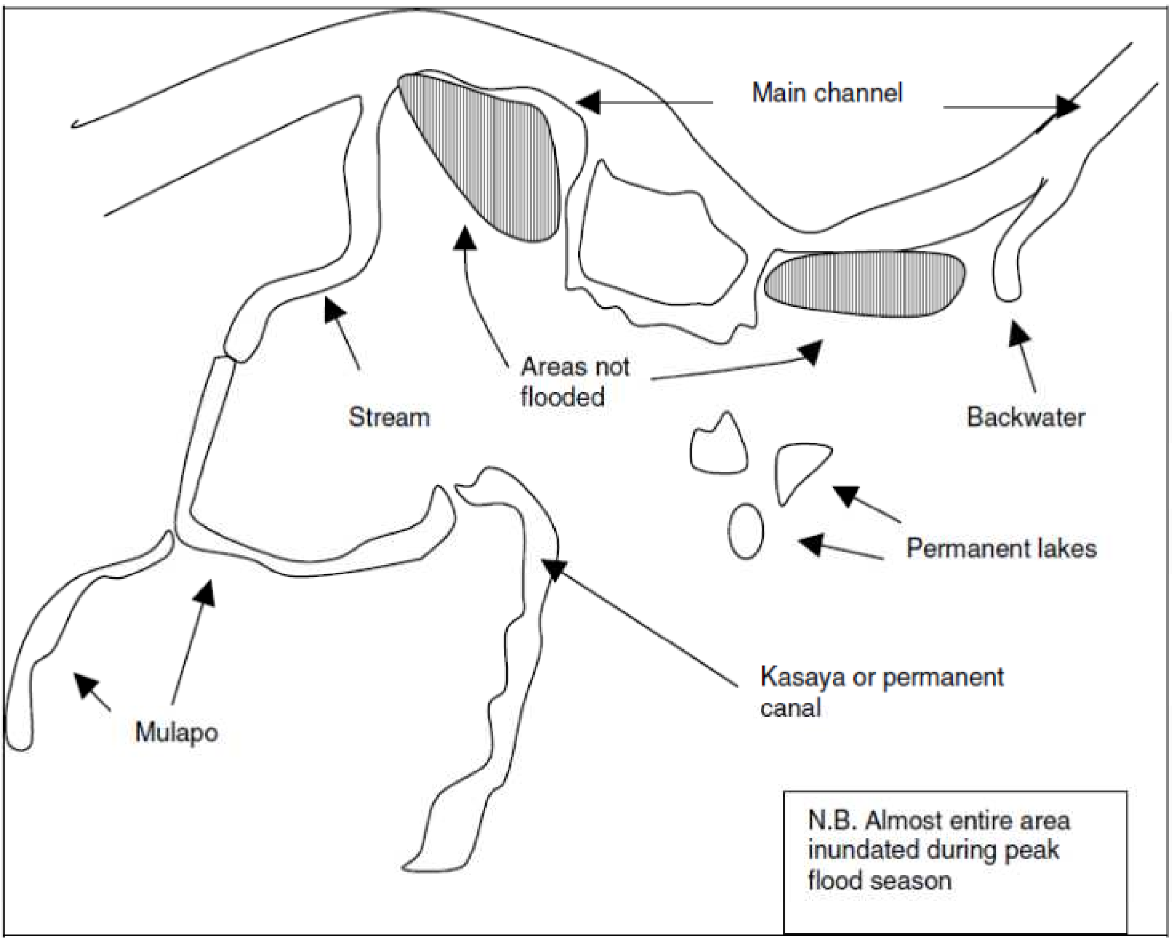

Figure 2: aquatic habitats available in Eastern Caprivi.
Source: Purvis, J. (2002). Fish and livelihoods: fisheries on the eastern floodplains, Caprivi. DEA Research discussion paper. Number 52. October 2002.

This figure represents aquatic habitats similar to those presented in our study area, which are explained in detail herein.

The figure could represent the Zambezi floodplain at the end of May, a month in which the water level begins to recede and the water bodies start to dry. Under such circumstances, the following habitats can be defined.

The main river channel (*nuka* is the local name), i.e. the Zambezi river. Streams (*kalamebas*) are the permanent small channels of water, running to the main channel, which show permanent flow and ensure fisheries throughout the year. A *kasaya* is a permanent channel or a canal that may or not be connected with the main channel. When both are connected, they do that through a *mulapo*, a seasonal depression which does not retain water throughout the whole year. A series of permanent lakes (*lisa*) are dotted across the floodplain far away from the main channel.

When the water level in the river increases during the wet season (starting approximately in the middle of February), the backwater begin to be filled and the flooded area grows. During this period, all the area is flooded and there is no different between the habitats described above. By June, the water level begins to decrease, and the aquatic environments become progressively drier, and much of the area is used for agriculture. During the dry season there is only water in the main channel, in the surrounding backwaters and in the lakes.

This sub-chapter focuses on mulapos, which are very important water bodies within the Chobe - Caprivi floodplain.

By definition, mulapos are ponds that retain water for a longer time than the rest of the floodplain. They can be found upon clay deposits from rich organic soils (higher concentrations of clay soil are typical in areas where the water is held for longer). In the Chobe – Caprivi wetlands, the mulapos receive water through the annual flooding and rainfall. When the water recedes, these depressions provide the chance for local people to use the water stored in them for agricultural purposes, using the residual soil moisture.

Because of this, mulapos are amongst the most valuable water bodies (Tvedten, 1994).

Four main categories of mulapos are recognized in the study area, as follows:

- **Permanent:** These areas are situated close to the Zambezi River and keep water during the dry season by subsurface connections with the river. Permanent mulapos tend to show very clear water, these are stable systems characterized by large populations of zooplankton (based for the food web)
- **Seasonal:** These tend to be further from the Zambezi River and are maintained by rainfall and seasonal floods from the river. Seasonal mulapos have similar limnological features to permanent mulapos, but conditions are more variable.
- **Episodic:** These are situated on higher ground or distant from the Zambezi River, and are maintained by episodic flood events and rainfall. The Bukalo Channel, which only receives water when the flooding reaches a certain level, is a typical example. There are no available biotic data on these systems. They are likely to be similar to seasonal mulapos, but with a lower biodiversity.
- **Periodically Connected Mulapos:** These are similar to endorheic pans, but they are occasionally connected to adjacent water bodies during years of high flow.

From an agricultural perspective, mulapos are very important for planting crops in the dry season (i.e. corn). Sorghum and millet are grown on the higher, non-flooded land. The production of corn is usually for subsistence purposes and sorghum is grown primarily for beer making.

There is a very little crop rotation practice and the use of fertilizer or manure is rare (Purvis, 2002).

Mulapos usually include carefully protected fisheries during the wet season. In some areas, they have an owner who can rent it. Within a silalanda (meaning “area” or a “neighborhood”), any resident can fish in any water body without asking permission. Within a silalo (several *silalanda* together, like a “district”), if someone wants to fish in a lake inside a silalanda different to that in which she/he resides, then it is necessary the permission from the “owner”. The “owner” is usually the head of the family of the village closest to the water-body, and, if the applicant is a resident of the silalo they cannot refuse permission. (All the information taken from: Purvis J., Abbott J., Næsje T. and Hay C. Share resource management on the Zambezi/Chobe systems in northeast Namibia: Current practices and future opportunities. Existing fisheries management systems and implications for future management.)

1.3 Environmental flows

The development and management of water resources by humans has altered the natural flow of rivers around the world. These actions may affect, for example the timing, frequency or duration of floods, and can modify the suitability of particular aquatic habitats.

The stream flow regime is a driving force in river ecosystems (Stanford *et al.,* 1996; Poff *et al.*, 1997). The stream flow is fundamental to the control of some hydraulic and biotic parameters of the river, such as depth, velocity, and habitat volume. There are strong connections between stream flow, floodplain inundation, alluvial groundwater movement and water table fluctuation because of the exchange of organisms, particulate organic matter, energy, and dissolved substances along the river system. The flow regime is also determinant for other fundamental factors of the river and wetlands ecosystems, such as temperature, dissolved oxygen, water quality in general and channel morphology.

The alteration of natural stream flow regimes modifies the riverine habitat, with adverse consequences for native biota (Poff *et al*., 1997). To avoid such situation it is necessary to define and evaluate alternatives of environmental flows, as well as to determinate strategies to implement, monitor and improve such flow regimes.

One definition for "Environmental Flow" is "the water regime provided within a river, wetland or coastal zone to maintain ecosystems and their benefits" (Dyson *et al.,* 2003). This definition was included in the Brisbane Declaration (2007), with a more general approach:

Environmental Flows describe the quantity, quality and timing of water flows required to sustain freshwater and estuarine ecosystems as well as the human livelihoods and well-being that depend on these ecosystems.

The accumulated research on the relation between hydrological variability and river ecosystem integrity, indicates that the range of natural intra-and interannual variation of hydrological regimes, and its characteristics of timing, duration, frequency and rate of change, are critical in sustaining the native biodiversity.

Because of that, given that the conservation of the ecosystem integrity is one of the aims of the river management, it should always consider specific flow rates for each month of the year, according to the natural low flows and the highest pulses throughout the year, and at the same time the inter-annual floods frequencies.

2 Objectives.

The main objective of this Master thesis is to investigate the importance of environmental flows in the wetlands of Eastern Caprivi (Namibia).

To support this investigation on the links between the hydrological and ecological processes, this work comprised the following partial objectives:

- To perform a bibliographic review of the previous hydrological research carried out in the Eastern Caprivi. Furthermore, similar research in other places was reviewed, in order to understand the hydrological and ecological system in wetlands and its behaviour.
- To describe the river network and wetlands in the Eastern Caprivi from a hydrological perspective.
- To perform the geographical location and mapping of the mulapos within the study area.
- To estimate the main parameters for the assessment of the environmental flow regime, under hydrological conditions of low flows and seasonal floods.
- To evaluate the potential impact of the hydrological alteration for a future situation of flow diversion for water demands.

3 Study area.

3.1 Zambezi River Basin. Caprivi Region.

The Zambezi River Basin is approximately 1.33 million km^2 in extent, and is one of the largest river basins in southern Africa. It lies across eight countries, with much of the basin covering Angola, Zambia, Zimbabwe, Malawi and Mozambique, and to a lesser extent in Namibia, Botswana and Tanzania. The Zambezi River is the fourth largest River in Africa after the Congo, Nile and Niger, and is the largest river system in terms of both area and flow volume. The Victoria Falls, one of the Seven Wonders of the World, are found on the Zambezi. Over 30 large dams in the Zambezi River Basin serve domestic, industrial and mining water supply, irrigation and power generation.

The Zambezi River arises from the Kalene Hills in Zambia, and flows south until it spills into the Indian Ocean, after flowing approximately 2650 km to the east, in Mozambique. Its numerous tributaries include the Kafue, Kwando (Cuando), Luangwa, Shire, Gwayi, Manyame and the Mazoe Rivers. The Luangwa is one of the few unregulated river systems, whereas the middle Zambezi has been dammed – with altered downstream environments. Despite all, the Zambezi River, its tributaries and associated ecosystems are considered the most important natural ecosystem in southern Africa (Ashton *et al*., 2001). Ten major wetlands are found in the Zambezi Basin. Due to the diversity of ecosystems, the basin is considered a regional centre of endemisms, being the Zambian portion one of the richest in Africa with 6000 species of plants, 650 species of birds and 200 species of mammals recorded (Chenje, 2000). Many of Africa's most renowned National Parks are found here, including Chobe National Park in Botswana, Kafue and Luangwa National Parks in Zambia, Hwange National Park in Zimbabwe, Liwonde National Park in Malawi and Gorongoza National Park in Mozambique. Its river systems support large numbers of people and encompass important conservation areas. Rivers also supply most of the Southern African Development Community (SADC) countries with hydropower: two of the largest dams in Africa are constructed across the Middle Zambezi - Kariba and Cahora Bassa.

One of the main objectives of this thesis is the calculation of the environmental flow using the data available in the gauging site of Katima Mulilo, in the **Caprivi region**. Therefore, here I focus on this region (more exactly in the Eastern Caprivi Wetlands) in order to make a hydrological description of the study area.

Figure 3 shows the general location of the study area while figure 4 shows the whole Zambezi River Basin.

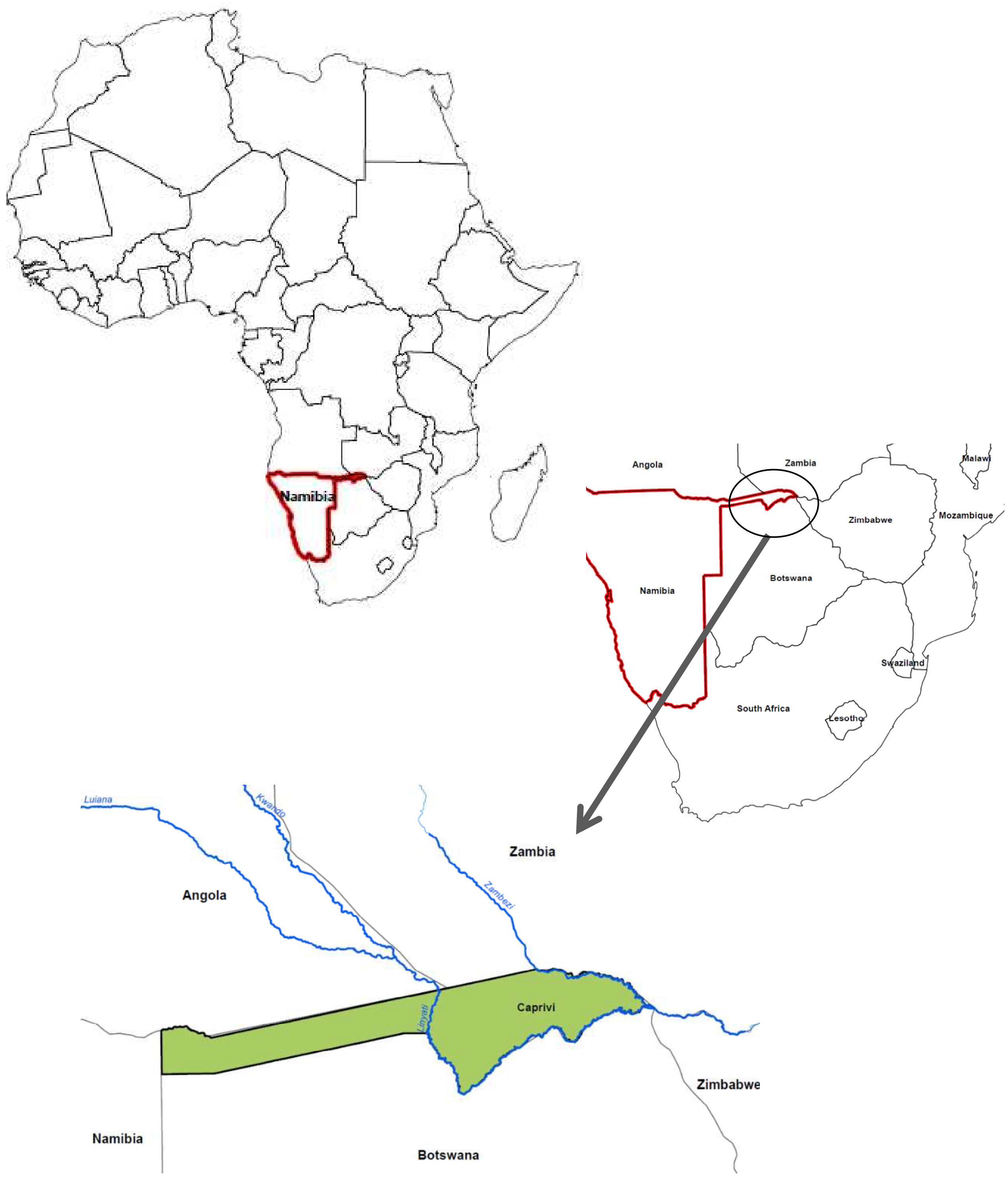

Figure 3: Location of the study area

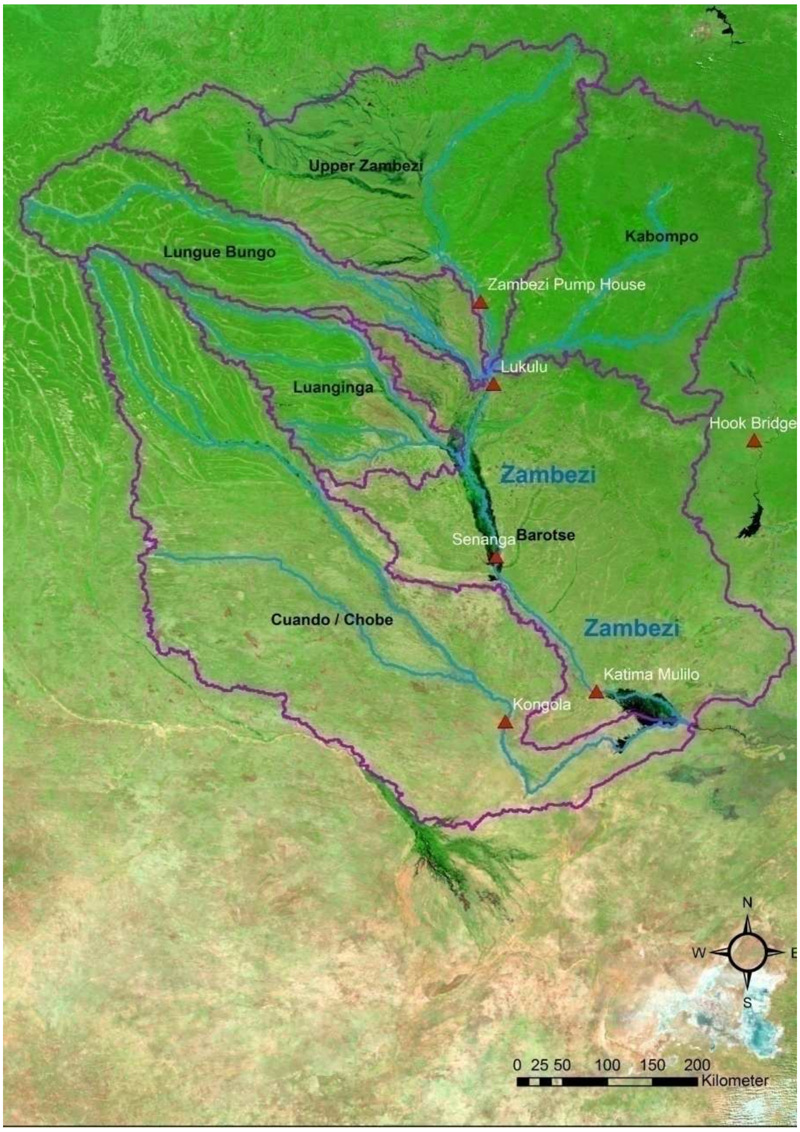

Figure 4: The Zambezi River Basin with stream flow gauging sites.

Caprivi is one of the 13 regions of Namibia. It is located in the far northeast of Namibia and can be considered as a large a floodplain area with an abundance of Wetlands.
Caprivi is almost completely surrounded by foreign countries. Only in the west it connects with Okavango; in the North, it borders to Angola (northwest) and Zambia (northeast) and in the South, it borders to Bostwana.

The borders in the Eastern Caprivi are created by the four most important rivers of the area: Kwando, Linyanti, Chobe and Zambezi. The whole region covers approximately 370.000 hectares, and 220.000 of them are considered wetland habitats (Turpie, 1999). The region gives home to about 110.000 people and is considered being one of the poorest in the country (*World Bank, 2010*). To provide an overview, Figures 5 and 6 show the most important features of the Eastern Caprivi.

Figure 5 shows Landsat Images of the Zambezi floodplain and the Zambezi and the Chobe rivers. It also shows the Bukalo channel that connects Zambezi floodplain with Lake Liambezi

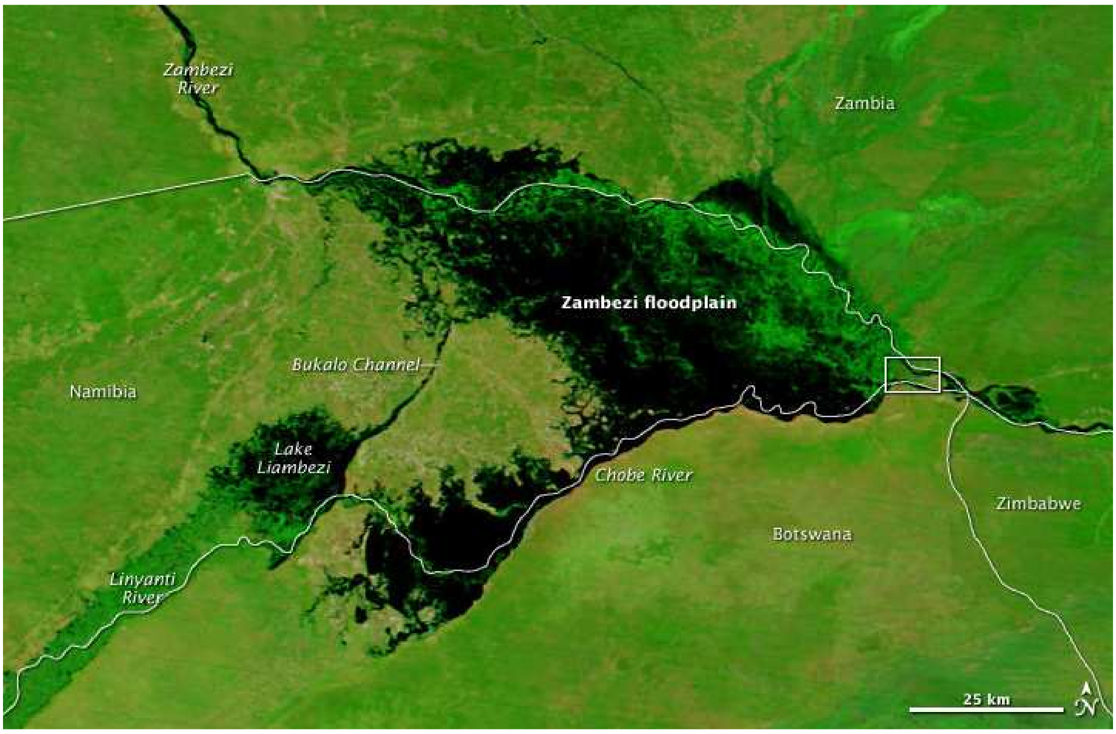

Figure 5: Features in the Eastern Caprivi

3.2 Physical environment. Topography, geology and land use

The physical environment of the study area is explained here using the subbasin scale. Moreover, after this description, different scales will be also presented to provide a better understanding of the study area, it exactly location and its main characteristics.

3.2.1 Subbasin scale

In the following lines, this scale will be use to define the physical environmental of the study area because it would properly represent the physiographic classes found in the Zambezi basin.

The figure 7 below shows the location of the river subbasins in the Caprivi region.

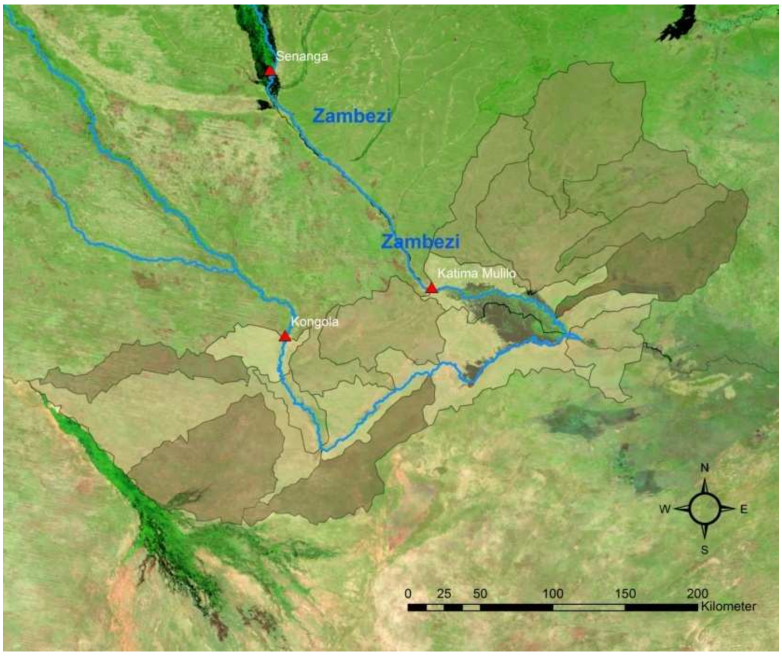

Figure 6: Map of the river subbasins in the Caprivi region (Namibia).

The Caprivi region is completely flat; there is not a single element recognizable as a hill (Turpie, 1999); the variations of the height are between 882 and 1310 meters above sea level (see map 1 in the annex 2).

Caprivi region lies in a sand pit commonly known as the Kalahari basin. The underlying soil types are predominantly clay-loam with small areas of sandy clay-loam and organic clay (Mendelson & Roberts 1997). Much of this basin is filled with sand deposited there by wind, with very little of the underlying geology exposed, except along river courses. That means that soils are generally poor in nutrients and its capacity to hold water is low. Because of that, crop yields are usually low (they normally use fertilizers) but are considered higher than elsewhere in Namibia because Caprivi receives more rain than other regions (Mendelsohn, 1994).

3.2.2 Regional scale

A Region is a broad geographical area with a common macroclimate and sphere of human activities and interest (Forman 1995). The spatial elements found in a regional scale are called landscapes.

The figure 8 shows the different features at regional scale:

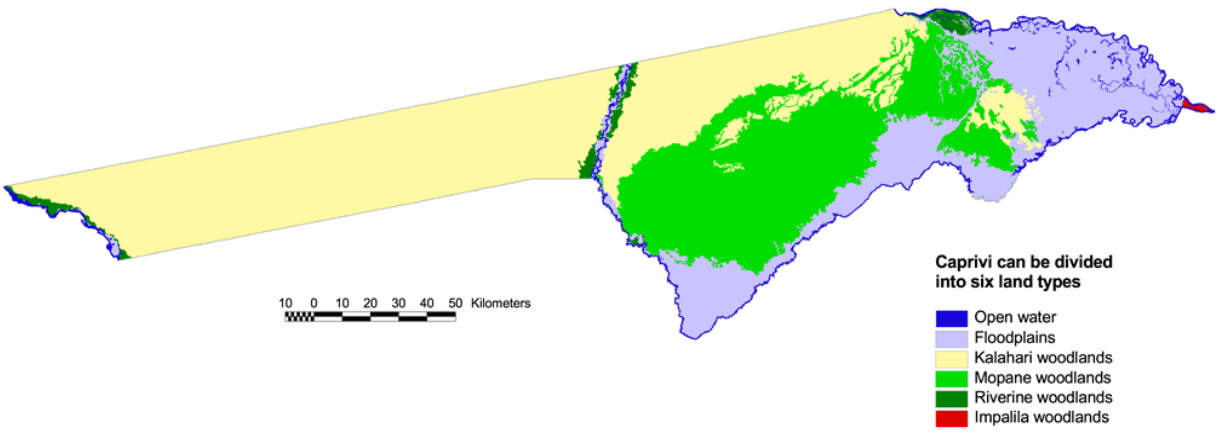

Figure 7: Caprivi map of land uses at a regional scale.
Source: Mendelsohn J. and Roberts C. (1997). An environmental profile and atlas of Caprivi. *Directorate of Environmental Affairs, Namibia, 1997.*

As seen in the figure, Caprivi can be divided into six land use types:

- **Open water**, which corresponds with surrounding rivers and also with the permanent wetlands system associated with open water and channels on the Eastern Caprivi floodplain.
- **Floodplains.**

- **Kalahari woodlands**, which covers most of the territory and consist mainly of deciduous trees and bush savanna.
- **Mopane woodlands**, with mopanes trees (*Colophospermum mopane*) dominating the vegetation, which are essential for both people and wildlife of the region. Most cultivation takes places in the Mopane woodlands, especially along the margins.
- **Riverine woodlands**, near the channel with riparian vegetation.
- **Impalila woodlands**, with an environment quite different from the other parts of Caprivi because of its basaltic rocks. The island has a high conservation value related to its high biodiversity.

Figure 8: wetland system in the Eastern Caprivi
Source: Matthias Beyer

Figure 9: Aerial view of the wetland area
Source: Matthias Beyer

Figure 10: Riverine woodland
Source: Matthias Beyer

3.2.3 Local scale

At a local scale, a geographic area is distinguished by a repeated pattern of components, which includes both natural communities like forest patches and wetlands, as well as human-altered areas like cropland and villages. "Local scale" patches in a map can vary in size from a few to several thousand of squared miles.

At the local scale, patches and corridors are usually described as ecosystems. The matrix is usually identified in terms of the dominant natural vegetation community, or land use dominant ecosystem.

In this study, a local scale patch corresponds to those in figure 6, showed above.

The four main types of units considered at that scale are these:

- **The river**
- **The floodplain and the swamps (where the mulapos are).**
- **The lake Liambezi**
- **The deciduous forest that surrounds the floodplains.**

Land cover and land use, are often used synonymously. Land cover refers to the actual coverage of the surface of the earth with natural or man-made environment (forest, grass, crops, water bodies, etc.). Land use refers to the use of the land cover (commercial forestry, pasture, etc.).

The land use and land cover maps are shown in the annex 2.

3.3 Main characteristics of the Mulapos and Kasayas

Mulapos and Kasayas were defined before as important features in the study area with special characteristics. Therefore in following lines the main characteristics are described, focuses mainly in the water quality, the amount of invertebrates and their biodiversity.

Water quality in mulapos is expected to vary considerably, both spatially and temporally, because of differences in size, depth, duration of inundation, etc. The water is similar to that collected in the Zambezi River, but the concentration of iron is six times higher and salinity levels slightly lower (7.7 mS/m). The high concentration of iron may be attributed to the mobilization of iron in organically enriched anoxic sediments that constitutes the substrate of the mulapo. The lower salinity is attributed to the mulapo being filled during peak flows, when the salinity in the Zambezi River would be expected to be lower than during low-flow periods. The concentration of chlorophyll A was seven times higher than in the Zambezi River, indicating considerable phytoplankton production. The quality of the water was considered high (Palmer, 2001)

The mulapos have a high diversity of submerged and floating aquatic vegetation. They provide ideal breeding grounds for snails, and 37 species representing 14 families have been recorded in these systems (Brown et al, 1992).

Should be noted that in the Caprivi region there is one endemic frog, the Mpacha grass frog (*Ptychadena mapacha*). It is dependent on perennial waters and will probably prove to have a wider distribution within the marshy habitat of the Caprivi region.
Palmer (2001) defined a classification for the ecological status of aquatic ecosystems in the eastern Caprivi based on a review of available data on aquatic ecosystems, discussion and a field visit. Based on this document, the main aquatic invertebrates in the mulapos are described herein.

The abundance of invertebrates is very low, and dominated by freshwater shrimps, specially by *Caridina nilotica*. The reason for the low abundance of invertebrates is unknown, but it is likely that predation by fish plays an important role in reducing invertebrate populations in the mulapo. Aquatic invertebrates were also collected from an open, permanent mulapo which is connected with the Bukalo Channel. The available habitats were restricted to marginal vegetation consisting of senescent grass. The diversity of invertebrates in vegetation was moderate, and dominated by damselflies (Coenagrionidae). The water column contained low numbers of zooplankton (mainly calanoid copepoda).

The aquatic invertebrates were also sampled from a permanent, clear mulapo where the aquatic vegetation consisted mainly of Bladderworts (*Utricularia sp.*). These plants have modified roots (bladders) with trap-door entrances that are seed to capture zooplankton and provide the plant with proteins (Muve, 1966). It was therefore not surprising that the water column in this mulapo had low numbers of zooplankton. In the vegetation, a moderate diversity of invertebrates was recorded, being dominated by Baetidae (*Cloeon* spp. complex) and Coenagrionidae damselflies.

Therefore we can conclude that in the mulapo, biodiversity is high and their conservation status medium, being the main threats the fishing, cultivation and livestock.

3.4 Hydrology and meteorology

3.4.1 Rainfall

In a country often characterized as hot and dry, the region of Caprivi is more tropical than any others. It enjoys a higher rainfall, less evaporation and warmer winter than in the rest of Namibia.

There are two different seasons: dry and wet season. The rainy season lasts from January to June; sometimes rains can start in the late November/December peaking from January through April (when about 80% of rain falls). In May rains usually stop and the dry season last from July to December. The rainfall in the upstream catchments of Caprivi is important for the creation of floods. However, because of the spatial variability of rainfall, it does not occur all the times that if Caprivi receives a good amount of rain, there is automatically a big flooding.

The precipitation data for the Caprivi region corresponds to the period 1902-2009 and came from the CRU Datasets.

In the table 1 in the annex 1, the mean and the sum of the precipitation for the study period are shown.

The mean of the total precipitation throughout the period is 646.46 mm. and the median is 629.87 mm. (Mediana de las medias anuales) → CRU_TS_31_Caprivi

3.4.2 Runoff

For the seasonal wetlands of Caprivi, the extension of the wetlands mostly depends on the amount of water entering the floodplain from upstream. There are several gauging sites in the study area, this work is based on the data from Katima Mulilo, located upstream the floodplain of Caprivi, in the Zambezi River. Data for this site could be obtained for a sufficient period of time to characterize the hydrological system in a greater detail. The measured flow is partially regulated, thus the flow is not determined only by rainfall, but also the abstractions upstream are affecting the flow regime. Another special feature of the system is that, due to the extended floodplains and wetlands in the Caprivi, where a great amount of water evaporates and percolates to the groundwater, there is a net loss of water within the catchment. There is no significant modification upstream the gauging station.

The following section concentrates on the analysis of the flow characteristics in Katima Mulilo gauging site.

The historical series data range from 1943-2011, excluding the years between 1955-1964 in which no data are available (Source: GRDC (*2011*) *Global Runoff Data Centre. Koblenz, Federal Institute of Hydrology (BfG).*

The Zambezi River system has a high variability as it shows in the figures 9, 10 and 11, indicating the mean annual flow, the highest annual flow –maxima- (HQ) and the lowest annual flow –minima- (LQ).

The following graphs were obtained by the calculation of the average, the minimum and the maximum daily stream flow from the available data of each year.

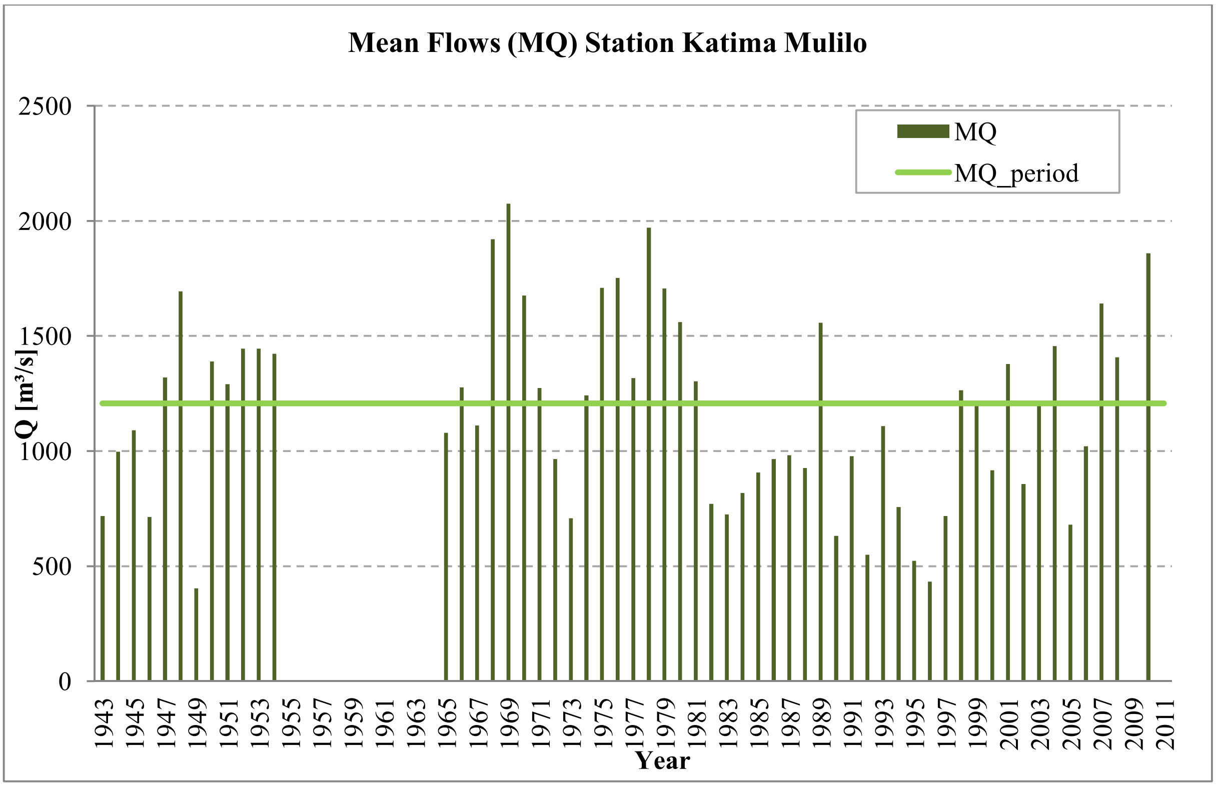

Figure 11: Times series of mean annual flow, by year. Station Katima Mulilo.

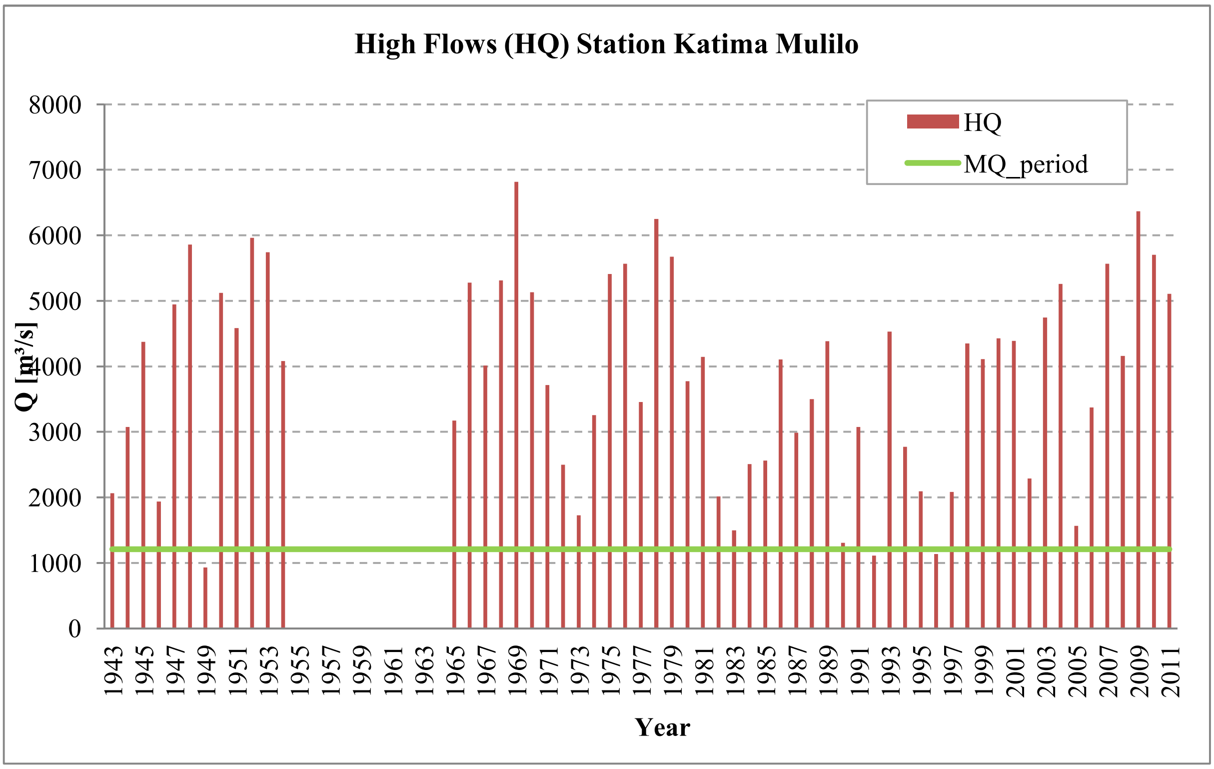

Figure 12: Time series of maximum annual flow, by year. Station Katima Mulilo.

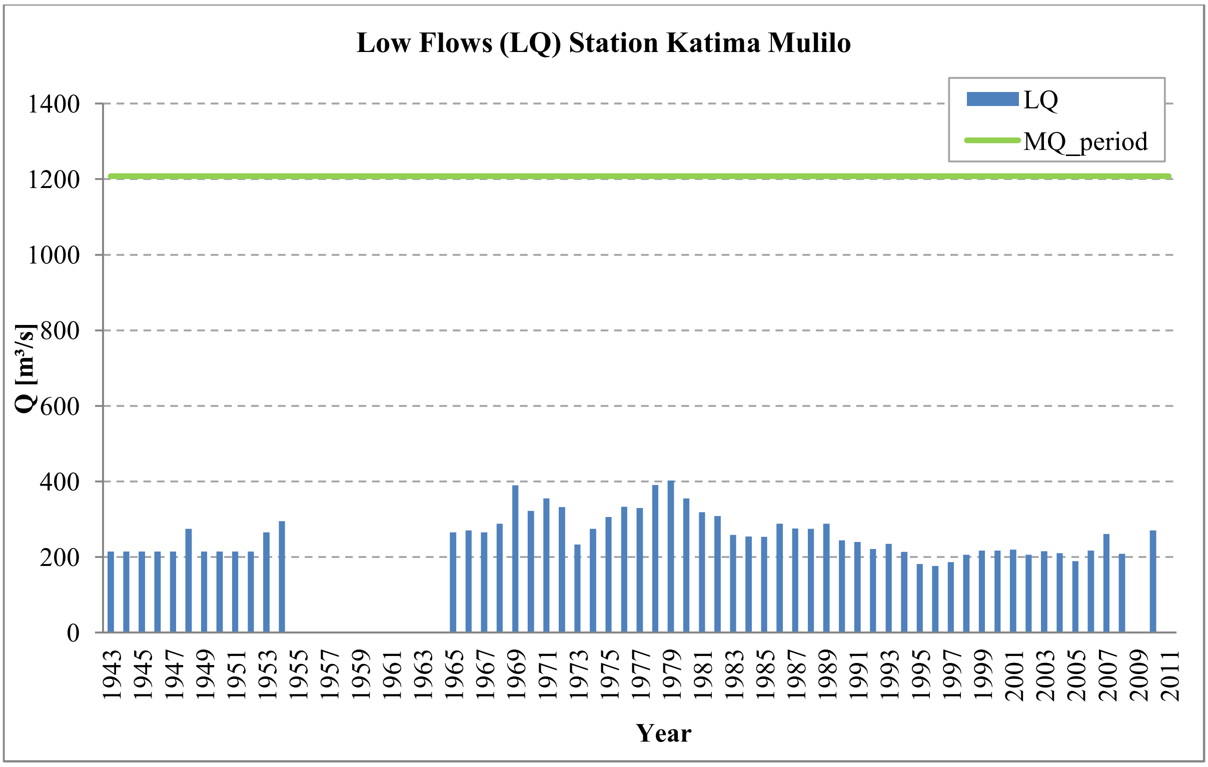

Figure 13: time series of minimum annual flow, by year. Station Katima Mulilo.

The average of the mean annual flow for the whole period is 1247.87 m^3/s. The average of the maximum annual flow is 3846.44 m^3/s and for the minimum annual flow, 269.47 m^3/s.

Figure 14 shows the monthly distribution of the stream flow within a year (monthly means).

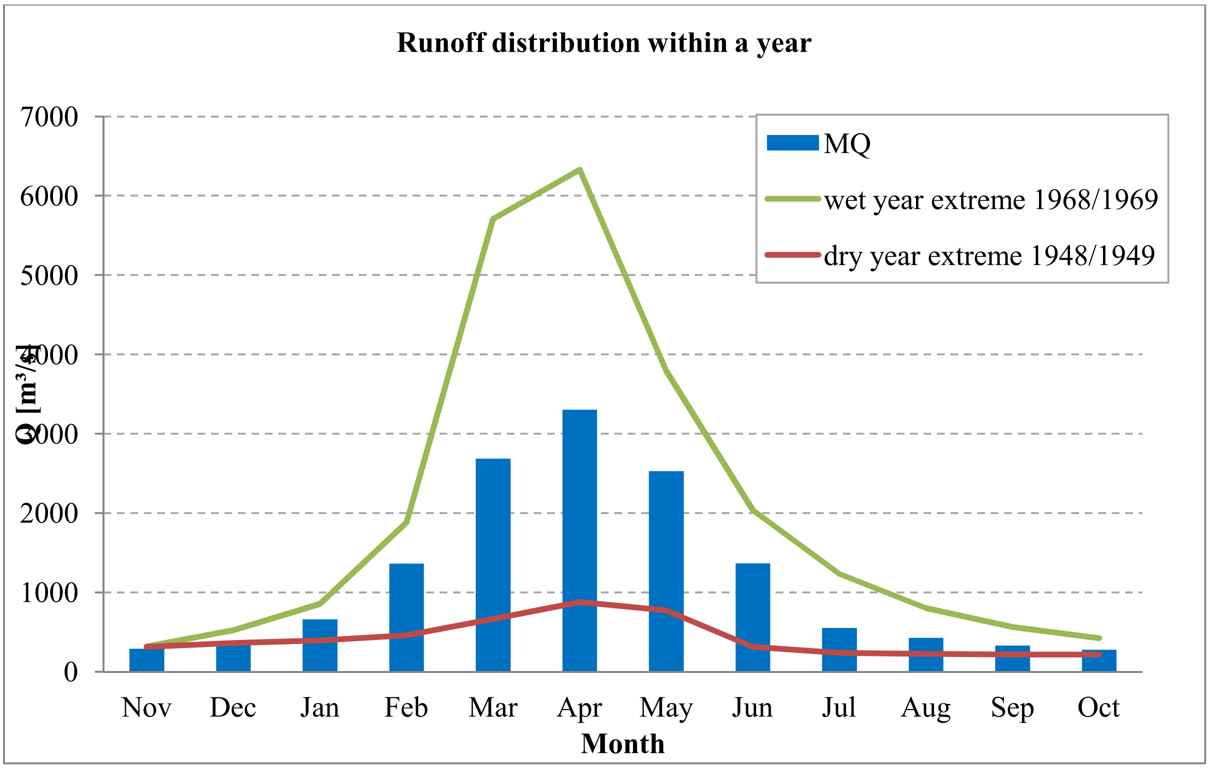

Figure 14: Mean runoff Katima Mulilo within a year.

The figure shows the annual cycle of runoff and identifies the months that are most likely to cause flooding as March, April and May. Flooding in the Zambezi starts as a runoff higher than 1350 m^3/s, river level 7.40 m, (World Bank, 2010). Likewise, the differences in water level between dry and wet season are very important, which means one of the most important ecosystem services of the wetlands: catch water during the wet season to be exploited during the dry period. The floodplain full of water at the end of the wet season, slowly releases it making it available for longer, and feed one of the most important touristic attraction in the whole Zambezi River; the Victoria falls.

A more detailed study of the flow in the Katima Mulilo gauging station is shown in the following chapters.

3.4.3 Air temperature

The Temperature data for Caprivi Region correspond to the period 1902-2009 and come from the CRU datasets.

The mean temperature for the whole period is 22.93 °C. The maximum monthly mean temperature is 26.58°C and it corresponds to October. The minimum monthly mean temperature is 17.06°C and it corresponds to June (mean statistical calculated).

The table 2, in the annex 1, shows the average temperature for each year

The following graph shows the mean annual temperature that occurred in the period between 1943 and 2001.

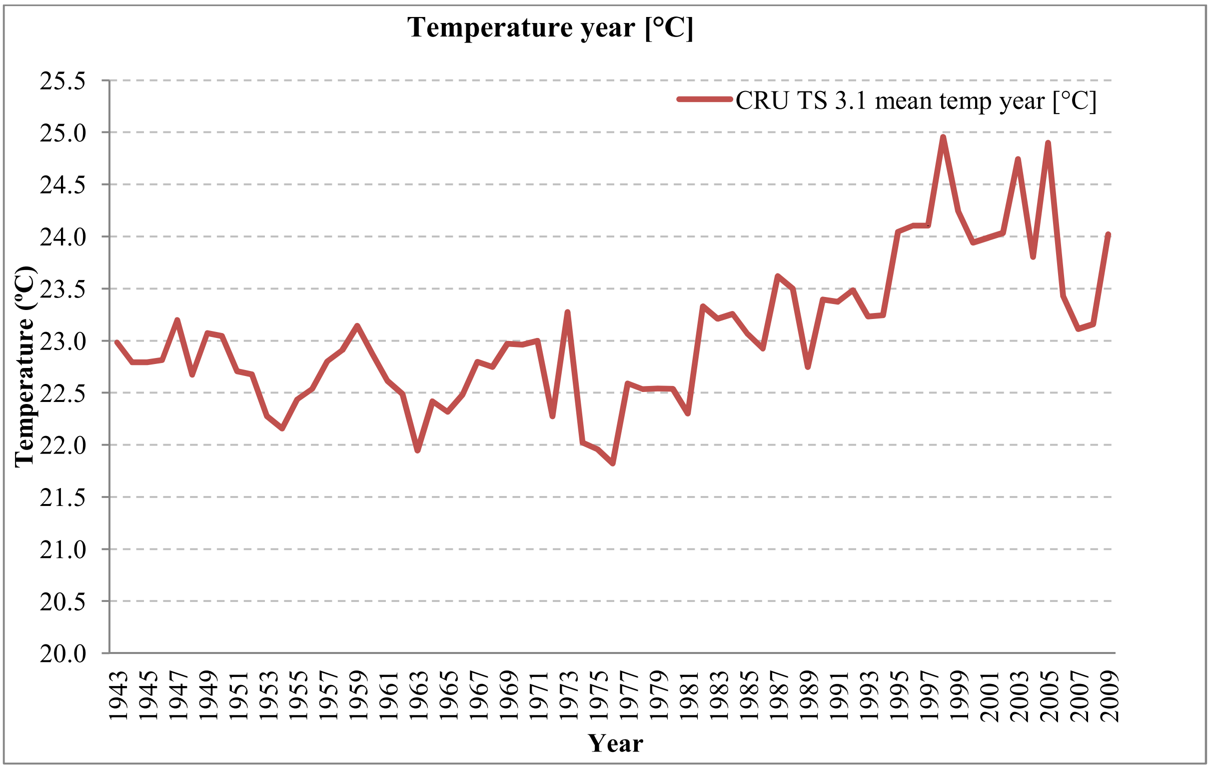

Figure 15: Time series of mean annual temperature, by year.

3.4.4 The potential evapotranspiration

The potential evapotranspiration data for Caprivi Region correspond to the period 1902-2009 and comes from the CRU datasets.

The mean potential evapotranspiration per year for the whole period is 1419.64 mm (mean statistical calculated).

The following graph shows the average annual evapotranspiration that occurred in the period between 1901 and 2009.

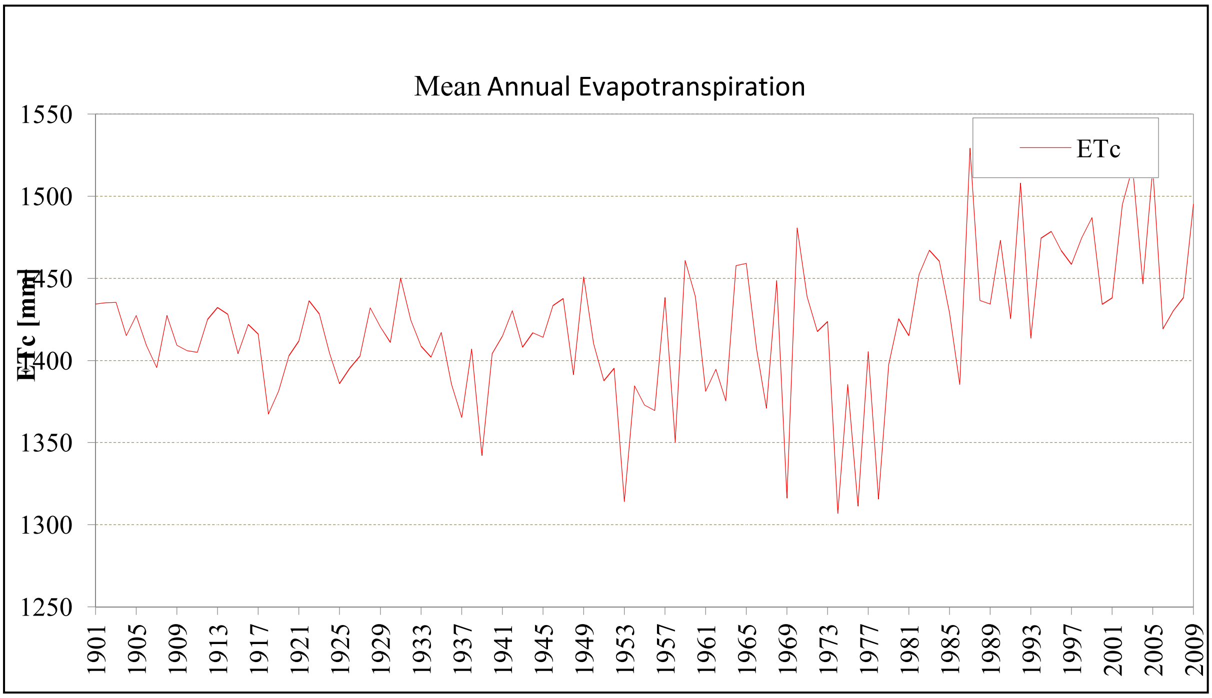

Figure 16: Time series of mean annual potencial evapotranspiration, by year.

The table 3 in the annex shows the mean annual potential evapotranspiration for each year.

3.4.5. The hydrological system

The data and analysis in this chapter is a synthesis of the information acquired from various sources and from various institutions (World Bank, FAO, etc.) that have carried some research in this region.

The Eastern Caprivi´s borders are created by the four most important rivers in the area: Kwando, Linyanti, Chobe and Zambezi.

The Kwando is born in the central plateau of Angola, on the slopes of Mount Tembo, then flowing southeast along the Zambian border. It is an almost pristine river; there is no research activity in its upper catchment. The river has unique hydrological characteristics with a high landscape value. It is also the habitat of many species.

Once the Kwando comes into Namibia, it flows through the Caprivi Strip across its marshy channel for about 35 Km heading then eastwards into the Linyanti swamps. At that place, the name of the river changes into the Linyanti River. It flows until the Lake Liambezi area and becomes the Chobe River, which further flows until its confluences with the Zambezi River in Impalila Island, the extreme eastern point of Namibia. After this confluence, the Zambezi River continues until the Victoria Falls, some kilometers downstream.

The Zambezi River is the seasonally dominant force and it is the state of the flow in that channel that determines the direction of the water flow in the Chobe, and consequently, the Linyanti (*Purvis*, 2002). In the flood season, when the Zambezi reaches its highest level, there is no significant flood in the Kwando River, but in the dry season the Kwando River rises slightly. This is because the Kwando is a river that flows almost the whole time through a wetland area (starting in Angola) which means that on one side there is no almost impact of the heavy rains in the wet season on the Kwando river (the wetlands acts as a sponge), and, on the other, a delayed response of the river flow to the heavy rains (the water gets lost in the way through the wetlands and some months after the rains, it is detected a slight increase of runoff in the Kwando).

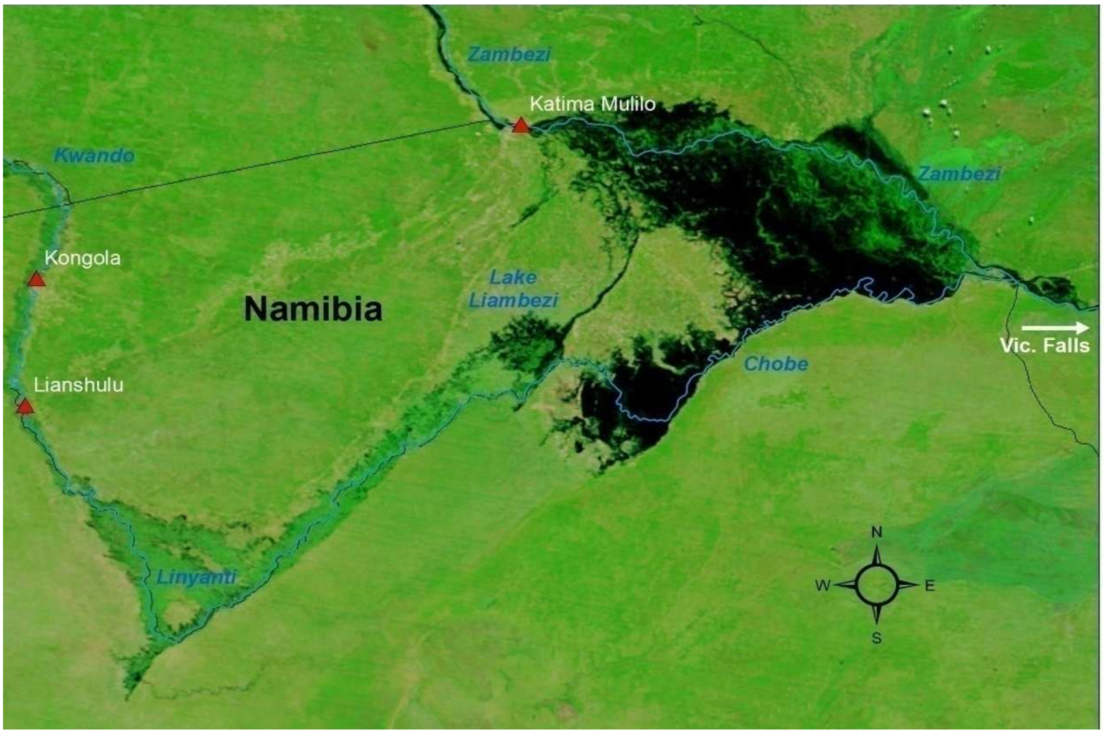

Figure 17: Wetlands in the Eastern Caprivi.

Figure 5 shows Landsat Images of the Eastern Caprivi during the flooding season and the catchment delineated from the namibian border to the outlet of the catchment (gauging site Victoria Falls).

The Lake Liambezi is also an important component of the system. It is a large and shallow depression situated near the confluence of the Chobe and Zambezi River (Rob Palmer, 2001). When the lake is full it can be as much as six meters deep, is a semi-endorheic lake and characterized by cyclic episodic of filling and drying. Its extension is about 260 Km2 (June 2011: 260 Km2. Source: Satellite image. Landsat-7), i.e., two times the extension of the Mar Menor, the largest coastal lagoon in Spain.

The lake was completely dry from 1985 until 2001 and it was used for extensive cattle grazing and for growing small crops of corn and sorghum (Rob Palmer, 2001). During the floods of 2001, the Kwando River reached a level much higher than in 1985, and the Lake Liambezi and some others channels and lakes received water that remained for several weeks.

Since then, the Liambezi Lake is periodically flooded receiving water from the Kwando River and sometimes from the Zambezi River through the Bukalo channel. When this happens the Chobe River might be force to flow in backward direction. In this case, water from the

Zambezi pushes the Chobe water back at the confluence of the two rivers. This inversion then causes the expansions of the wetlands around the Chobe until the water reaches the Lake Liambezi.

The floods generally follow a patter within a year. There used to be two time periods with floods. One of them is at the beginning of the wet season (February or March) after which the river breaks its banks and the floodplain start to be flood. The water level in the channel seems to decrease and then began to rise when the water cannot be longer accumulated in the floodplain. By the middle of May, the floodwaters begin to recede. It is estimated that the water remains at its highest level for only about two weeks, depending on the conditions (Purvis, 2002).

The area covered by the water and its highest level varies but it estimated to cover about 30 per cent of the area of Caprivi (Turpie, 1999). The floodplain system in the eastern Caprivi forms a continuous area of approximately 370 000 hectares, linking the Kwando, Linyanty, Chobe and Zambezi River (Turpie et al. 1999). The water forms a variety of drylands and wetlands areas, described here in previous chapters.

These natural patterns of hydrological behavior must be completely respected and any management plan in the area should consider it. Any impact on the timing and duration of the floods could affect the ecosystem and carry socio-economic consequences for people who depend on it.

3.5 Ecological characteristic and biodiversity of the floodplain

In general terms, Caprivi Strip is a nationally important ecoregion with a conservation status of “relatively intact” and a conservation priority class of V (World Bank, 2010). Conservation class V means that the study area is a bioregionally outstanding and nationally important ecoregions with relatively intact aquatic system. This classification is based on biological distinctiveness and conservation status. It goes from status I, that refers to an ecosystem highly threatened, to status V (Thieme and others, 1999).

Vegetation consists mainly of floodplain types, with flood grassland and swamp vegetation. The open water channel is formed by dense stands of many reed (e.g. *Phragmites australis*) and sedge (e.g. *Cyperus papyrus*) species, varying in size as the floodwater rise and fall. The floodplain grassland contains a mosaic of grasses (e.g. *Eragrostis spp.*, *Hyparrhenia spp.*, *Tristachya superba*) and the wetter soils are dominated by extensive lawns of *Cynodon dactylon* which form an important grazing resource for wildlife and livestock (Turpie et al. 1999). This are intermixed with a mosaic of woodlands predominantly by *Terminalia sericea* woodlands Mendelsohn & Roberts 1997).

This ecoregion provides a good place for breeding and feeding for a rich set of fish species and herpetofauna. The floodplain fish migrated onto floodplains with the first floods to spawn. Fish communities are dominated by cyprinids, cichlids and mockokid catfish. In terms of herpetofauna the ecoregion is richer in species than others, including at least, one frog endemic *Ptychadena mapacha* (world Bank, 2010). The most common species caught by fishermen are shown in the table 5 below.

Table 1: The most common species caught by fishermen.
Source: Purvis, 2002

Local name	English name	Scientific name
Ndombe	Catfish	*Clarias gariepinus*
Lubango	Silver catfish	*Schilbe intermedius*
Ngweshi	Tigerfish	*Hydrocynus vittatus*
Njinji	Threespot tilapia	*Oreochromis andersonii*
Muu/Imu	Greenhead tilapia	*Oreochromis macrochir*
Mbufu	Redbreast tilapia	*Tilapia rendalli*
Situhu	Banded tilapia	*Tilapia sparrmanii*
Siyeyo	Green happy/pink happy	*Sargochromis giardi*
Mushuna	Thinface/Humpback largemouth	*Serranochromis angusticeps*
Nembwe	Nembwe	*Serranochromis robustus*
Ngenga	Purpleface/Brownspot largemouth	*Serranochromis thumbergi*
Ndikusi	Western bottlenose	*Mormyrus lacerda*
Nembele	Bulldog	*Marecusenius macrolepidotus*
Ninga	Churchill	*Petrocephalus catostoma*
Singonggi	Squeaker	*Synodontis spp.*
Mulumesi	African pike	*Hepsetus odoe*

Water birds also occur in large congregations, reed cormorant (*Phalacrocorax africanus*), storks (*Anastomus lemelligerus*), Caspian plover (*Charadrius asiaticus*) and whiskered tern (*Chlidonias hydridus*). Mammals such as the red lechwe (*Kobus leche leche*) and sitatunga (*Tragelaphus spekei*) are now confined to protected areas (World Bank, 2010).

3.6 Livelihood and socio-economic aspect

The population in the Caprivi region is about 80.000 (year data 2004. World Bank, 2010). Katima Mulilo, the capital of the Caprivi Strip, had 22.134 inhabitants in 2001 (Windhoek: Central Bureau of Statistics, National Planning Commission. *Republic of Namibia 2001 Population and Housing Census (Basic Analysis with Hightlights ed.)*. July 2003), but it is estimated to have risen to 28.100 in 2010. Population density is generally higher along the river and near the floodplain and water bodies due to the relatively high potential for diverse use of natural resources.

Caprivi is rated as the poorest region in the country with the lowest human development index (Purvis, 2002).

Most houses are in the floodplain themselves, some in the woodland area adjacent to the floodplain (Mendelsohn & Roberts 1997, Ashey & LaFranchi 1997). The permanent structures are located in the higher places, which are not inundated during the normal year flood.

The livelihood is mostly determined by the yearly cycle of floods, necessary for subsistence but also considered as a problem by the people living there. The population strategy for coping with this situation is moving during the wet season to higher campsites that were built by the government for this purpose. When the floodwater recedes, they come back to their houses and start with the agricultural tasks.

The subsistence agriculture could be considered as the dominant employment in the study area. Livestock rearing and fisheries, especially in the floodplains, are prominent. There are another livelihood activity includes cropping, horticultural practices, tourism activities, home-based productions, etc.

As noted above, the major part in the area is flat and therefore regularly flooded so any kind of activities are related with the flood cycle. In the table below are shown the main activities in the Caprivi region in base of the time of the year.

Table 2: main activities of the people in Caprivi.
Source: redrawn after Turpie, 1999.

Activities of the people in Caprivi in regard to the annual flooding												
Month	**J**	**F**	**M**	**A**	**M**	**J**	**J**	**A**	**S**	**O**	**N**	**D**
Flood season		■	■	■	■	■	■					
Fish on floodplain		■	■	■	■	■	■	■	■	■		
Maximum fish catch			■	■	■	■	■	■	■	■		
Cattle on floodplain	■	■					■	■	■	■	■	■
Reeds harvested							■	■				
Grass harvested							■					
Palm harvested								■				
Wild plants harvested							■	■				

The extremely floods can be devastating but at the same time are essential for people who are living there because they provide numerous benefits. The provision of fishes as nutritional source is one of the most important benefits, as well as the grazing area during the dry season for approximately 124.000 cattle (World Bank, 2010). There are also indirect values as the recharge of the groundwater or mitigation of floods as has been explained in the chapter 1.1, the importance of wetland and floodplain.

Within these activities, there are clearly some of which are more important than others, but the importance is determined by the services/goods which the activity provides to the household. This will change from month to month, between years, between households and within households (Purvis, 2002). In the next table, the main activities for livelihood and their timing are tabulated and schedules in more detail.

Table 3: main activities for livelihood and their timing in the Caprivi region.
Source: Purvis, 2002.

Month	Nov	Dec	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct
River condition		River levels rising (through the rainy season) slowly to break banks by March and reach peak in May						"Drawdown" season as water moves back to channel			Low water period until November	
Fishing	Drag netting in isolated pools; channels very lucrative in the low water season											
				Gill netting across floodplain as water fills the river and fish move to the plains for feeding and spawning								
						Women and children involved in using traditional gears on the inundated plains						
								Fishing activity intensifies as flood water recedes				
River-field crops		Harvest (Dec), may continue to Feb. Completed before highest water levels							Preparing and planting fields as the water recedes (Sept.)			
										Weeding activities		
Dryland crops	Prepare and plant fields for first rains in November					Harvest complete by late May						
			Weeding activity is ongoing									
Livestock	Abundant grazing in lush forest areas with rain giving easy access to water						Cattle move onto the plains as water recedes				Grazing and water in short supply	
Horticulture							Main planting period for vegetables				Vegetable harvest	
Home-based industries	Ongoing throughout the year											
	Wild fruit collection at peak in early rains					Collection of wood and poles from the forest areas						
Wildlife/tourism								Main sport season for bream fishery-angling				
										Peak tourism season, particularly on the Chobe River (thru Nov)		

3.7 Threats in the Caprivi subbasin

The Zambezi River Basin and specifically the subbasin of Caprivi are rich in water and natural resources. Anyway, there are some threats to the sustainability of these resources; the most important are summarized below.

The historical data of the hydrology of the Zambezi River show that floods and droughts have been occurring in the past and are usually cyclic. However, in some cases they may represent problems for the maintenance of the natural resources. Extremely floods destroy crops, infrastructure, wildlife habitats and in some cases humans lives. Drought could also be as devastating as floods, in terms of reducing food production or cause damage to the wildlife and the wetlands ecosystem.

Wetlands are amongst the most sensitive areas in a basin, and the ecosystem services of them are threatened through water pollution and uncontrolled and unmanaged use of water (Mott MacDonald, 2007). The water pollution affects negatively to the aquatic life and ecosystem in general, decreasing the water quality and increasing the eutrophication process in lakes and reservoirs. The eutrophication increases the growth of invasive weeds like water hyacinth which impact negatively on the water use. Mainly, the water pollution is due to agriculture activities, livestock, mines, towns and industries, and also implies problem for reproduction and fish growth.

Other pressures to the natural resources due to the increase of the human population are mainly the increase of the livestock grazing which means an increase of the soil erosion and the overfish and illegal fisheries.

The climatic change is also a threat for the Caprivi wetlands and its natural resources. However, beyond this complexity, there are two main statements: dry areas will get dryer and wet areas wetter, with important consequences for the distribution of the agricultural production. There will be an increase in the unpredictability of floods, linked to more frequencies and extreme events (Mott MacDonald, 2007).The temperature in the Zambezi basin increased 1-2 °C between 1970 and 2004 (IPCC). So far, there is no evidence of long-term change in seasonal rainfall or increase variability. A reduction of runoff in the recent years is now evident (Mott MacDonald, 2007). The impact of climate change in the region concerns the evaporation from reservoirs, agricultural productivity and fish production, this means problems relating to the availability of food and with the management of the natural resources.

The poverty is also a threat for the sustainable management of water resources. In the Zambezi River Basin, on average, 70 % of the population is rural and poor due to some different causes like poor economic government policies, corruption, inadequate access to land and capital, little capacity to defend against some effects of floods and droughts, and poor prioritization of use of available resources by government. That implies negative consequences in the natural resources for some reasons, such as the acceleration of the process of land degradation. Poor agricultural practices are prevalent because of the limited agricultural inputs and the poor equipments that means an increase of soil erosion and contributes to the water pollution. In the same way, there are no opportunities for using alternative energy sources and rely entirely on firewood and charcoal, thus the forest are being destroyed, leading to deforestation and land degradation (Michael J. Tumbare, 2004).

As explained above here, the Zambezi River Basin, and of course the subbasin of Caprivi has its threats but also its opportunities. It turns necessary to identify all of these threats and establish mitigation measures for the benefits of the population and to ensure the sustainability of the natural resources in the area.

4 Methods

In order to achieve the objectives of this Master thesis, a variety of methods has been applied. They are explained in this chapter, starting from the hydrological characterisation, until the assessment of environmental flows.

4.1 Hydrological characterization of the river flow pattern

The chapter 3.4.1. Runoff, shows the high variability of the flow in the Zambezi River. As shown in the figures, there is a huge variability between the mean, the high and the low flows within a year.

A more specific study about the hydrological characteristics of the river in the Katima Mulilo gauging site was carried out. For this purpose, the historical data series from 1943-2011 was used (excluding the years from 1955-1965 with no available data), provided by the *Department of water Affairs, Windhoek (DWA), Namibia.* The whole data series has a daily temporal resolution, i.e., each data means a mean daily stream flow.

The duration curve for the whole period was made. It shows the percentage of time during which specified discharges have been equaled or exceeded in a given period and also shows the flow rate in function of the frequency of its occurrence (Searcy, J. K. (1950). Flow duration Curves. Manual of hydrology: part 2. Low-flow techniques. *US Geological Survey, water resources division*). Such curve can be used to show the percentage of time when river flow can be expected to exceed a design flow of some specific value, or to show the discharge of the stream that occurs or is exceed some percent of the time. It has been made based on the daily flow for the whole period with available data, using the following method:

1. Sort the values of the daily discharge of the period from the largest value to the smaller value, involving a total number of “n” values.
2. Assign each discharge value a rank (M), starting with 1 for the largest daily discharge value.
3. Calculate exceedence probability (P) as follows:

$$P = 100 * [^{M}/_{(N+1)}]$$

P= the probability that a given flow will be equal or exceeded (% of time)

M= the ranked position on the listing (dimensionless)

N=the number of events for the time period (dimensionless)

Different years are divided into "extremely wet", "wet", "normal", "dry" or "extremely dry" year. Depending on the data considered (runoff or rainfall) the classification of the year will be different. For instance, a year could be "dry" in terms of runoff, but could be "normal" based on precipitation criteria and vice versa.

With regards to runoff, the classification depends on the value of the flood volume in km^3 for each year (which is linked with the highest flow recorded and physical observations). This is because of the importance of the floods in the study area. Flooding in the Zambezi occurs when runoff is higher than 1350 m^3/s (World Bank, 2010); thus, taking the daily runoff data for each year, the amount of runoff exceeding this threshold can be calculated. These daily values are summed up and transformed from m^3/s into km^3, providing the basis for the classification of the years ranging from "extremely dry" to "extremely wet". The values go from 0.0 until 34.26 Km^3, and the classes in the next table.

Table 4: Classification of the years in the time series according to the flooded volume (water volume flowing over the banks in a year)

class/criteria	**flood volume [km³]**	**Maximum peak flow HQ (*) [m³/s]**	**Flooding conditions in wetlands**
very dry year	0	<1350	no flooding
dry year	0–7.5	1350–3000	-
normal year	7.5–17.5	3000–5000	-
wet year	17.5–30	<5000	no spill into Lake Liambezi
very wet year	>30	>5000	flooding with spill into Lake Liambezi

(*) Highest monthly discharge

Concerning precipitation, the criteria for classifying a year as wet or dry change based on official criteria from the paper: "A Continental Scale Classification of Rainfall Seasonality Regimes in Africa Based on Gridded Precipitation and Land Surface Temperature Products" (Stefanie M. Herrmann, Karen I. Mohr, July 2011). This paper adopted an approach from Walter and Lieth´s (1960) in which they relate monthly rainfall and temperature to define arid and humid months in Africa. They define an arid month as one in which the precipitation "P" in millimeters is less than two times the Temperature "T" in degrees Celsius ($P<2T$). In humid months, the precipitation exceeds two times the temperatures ($P>2T$). This is because 2T has been found to be linearly related to annual potential evapotranspiration, based on data collected from lysimeters across different climates zones; thus 2T can be used as an approximation for evapotranspiration (LeHouérou, 1996, 2010).

Taking into account this criterion, if the precipitation value for one year is greater than two times the mean yearly temperature (and multiplied by 12), the year will be wet. If the value is smaller, the year will be dry. The temperature and precipitation data from CRU TS 3.1 (Jones & Harris, 2008) were used.

At the same time and due to the importance of the floods in the study area, the recurrence interval (in years) of the maximum annual flow (m^3/s) was calculated using the historical data series from 1965 to 1999 and the software IHA.

4.2 Determination of the Mulapos using remote sensing

Remotely sensed imagery has long been used in water resources assessment and coastal management. These applications have involved the delineation of open water using extraction techniques on the thematic information. In the following paragraphs, several activities that were carried out in this Master Thesis, all of them within the framework of GIS and remote sensing, will be explained, with the aim at identifying the water bodies (mulapos) in the study area.

This subchapter will focus on the determination of the water bodies (mulapos) using remote sensing techniques.

Regarding the methods available for the extraction of the water bodies, they can be separated into two main categories, according to the number of bands used: single band or multi-band methods. The single-band method usually involves choosing a band from a multispectral image to extract open water information (Rundquist et al.,1987). A subjective threshold is then determined to distinguish between water and land, which may lead to an over- or under-estimation of the area, often mixed with shadow noise.

The multi-band method uses the reflective difference of each involved band, extracting the water information by the use of two multispectral bands. One is taken from visible wavelengths and is divided by another band, usually from near infrared (NIR) wavelengths. As a result, vegetation and land presences are suppressed while water features are enhanced. Under this umbrella and following this theory, the mndwi index is constructed.

The Normalised Difference Water Index (NDWI) is derived using similar principles to the Normalised Difference Vegetation Index (NDVI). In an NDVI (comparison of differences between red and infra-red bands), the presence of terrestrial vegetation and soil features is enhanced while the presence of open water is suppressed because of the different ways in which these features reflect those wavelengths (McFeeters, 1996):

$$NDVI = (NIR-Red) / (NIR + Red) \tag{1}$$

If the equation is reversed and the Green band is used instead of the Red band, then the vegetation will be suppressed and the water will be enhanced. Thus, the NDWI index is expressed as follows (McFeeters, 1996):

$$NDWI = Green – NIR / Green + NIR \tag{2}$$

In this expression, *Green* is a green band, such as TM band 2 (using images from Landsat; the bands can vary depending on the satellite's sensor), and *NIR* is a near infrared band such as TM band 4.

The selection of these wavelengths maximizes the reflecting properties of water:

- Maximise the typical reflectance of water features by using green wavelengths,

- Minimise the low reflectance of NIR by water features, and

- Maximise the high reflectance of NIR by terrestrial vegetation and soil features.

Using this index, an images is obtained in which it is possible to identify water features because of their positive values while vegetation and soil are suppressed because of their zero or negative values (McFeeters,1996).

However, when this index is used in regions with built-up land, a problem is found. The reflectance pattern of built-up land in the Green and NIR band is similar to that of water, producing positive values for these features as well, making it difficult to distinguish between water and built-up land in the raster images of NDWI. Detailed examinations of the figures reveal that when using the middle infrared (MIR) band instead of the NIR band, the reflectance of built-up land is reduced. Therefore, a MIR band is used instead of the NIR band in the NDWI, giving the built-up land a negative value, which makes it easy to differentiate between water and other features (Hanqiu Xu, 2006).

Based on this assumption, the NDWI is modified into the MNDWI that can be expressed as follows:

$$MNDWI = Green – MIR / Green + MIR \quad (3)$$

To determine the water bodies in the study area, firstly all the bands corresponding to the target image were downloaded from the USGS website (www.usgs.gov), and the software ArcMap (Copyright © 1999-2010 ESRI Inc. All Rights Reserved) was used for image processing (using the raster calculator and following the formula (3) described above), the watershed delineation and the volume calculation, as it will be explained in the following lines.

First, the location of the mulapos in the Caprivi-Chobe wetlands was determined. For this purpose, a satellite image (Landsat 5) from May 2008, a really wet year with image available for almost every month, was used. The month of May was chosen because it corresponds to the end of the wet season; rains have stopped and the remaining water indicates the lower areas where the mulapos are. The Modified Normalized Difference Water Index (NMDWI) will be used for this purpose.

Once the mulapos were located, the satellite images of the years between 2000 and 2011 (representative of the current climatic conditions) were used to determinate how often the mulapos were flooded (using, in this case, the images in April for each year, which corresponds to the highest flood of the year).

For this task, first the MNDWI (Modified Normalized Difference Water Index) was determined for each year, as explained above, showing the location of the water bodies.

Due to the huge extension of the study area, the floodplain was divided into 12 sectors, based on the following criteria: there is a sub catchment division between Katima Mulilo and Victoria Falls, as shown in figure 6. This was done with standard watershed delineation, with the help of the Digital Elevation Model (DEM) in GIS, and means that the division is made based on the direction of water flow: on one side water is flowing towards the Chobe River and on the other side towards the Zambezi River.

Taking into account this natural division, the floodplain was divided into 6 equal segments, which are crosscut (overlaid) by the subcatchment division, resulting in the 12 sectors shown in figure 18.

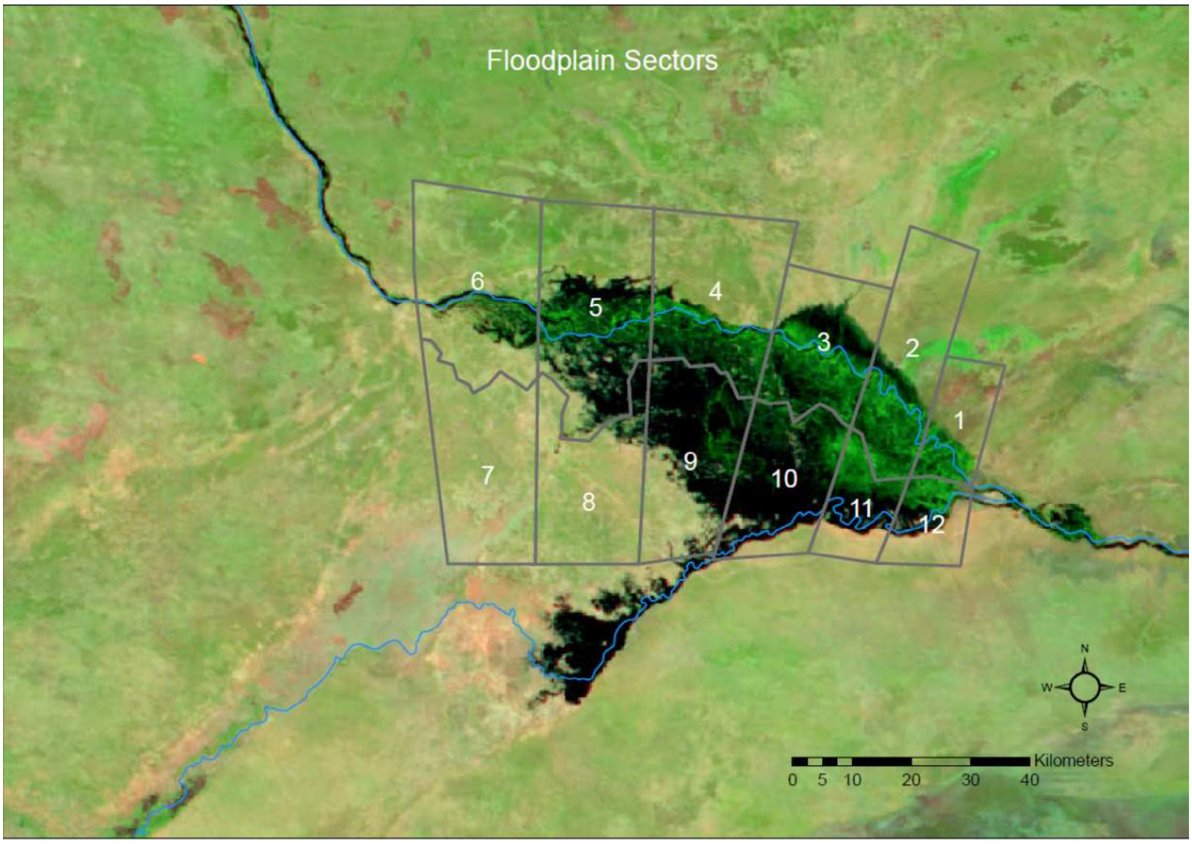

Figure 18: Floodplain Sectors (12) considered for the spatial analysis of the floodplain and delineation of the mulapos.

4.3 Calculation of the water volume of the floodplain

Once the water bodies in the floodplain were determined, the water volume that remains in the floodplain during the month of April was calculated. Thereafter, a comparative assessment of the flooding in different years in each polygon was carried out, in order to identify how often they had been flooded in the past 10 years.

In the MNDWI images developed, the floodplain, the river and some clouds can be observed. In order to be more accurate in the calculation, the river and the clouds should be eliminated from the image. In the case of May 2008 this is relatively easy to do, because the different features are well determined. However, for some images this is very difficult due to the amount of water remaining, which makes the boundaries very fuzzy. For this reason, it has not been possible to complete this step for all the satellite images.

The volume calculation was realized for the floodplain for each year, based on the following methodology.

Firstly, the water level was determined, using the DEM and the MNDWI raster layers (images) and following these steps for each satellite image.

1. The MNDWI index is transformed into a polygon layer and cropped with another polygon layer (previously done) of the floodplain, using the *Clip Tool*. The clouds are eliminated in this step.
2. With the use of the DEM and the layer obtained previously, thought the *Extract by Mask Tool*, a raster image will be obtained which will be converted into a polygon layer.
3. The polygons that correspond with the flooded area (obtained in the first step) will be transformed into a line layer.
4. After that, both polygon and line layers were crossed and the most frequent GRIDCODE value was identified, which corresponds to the water level.

Once this value was determined, the water height of each pixel (shown in the attribute table of the DEM) was deducted from the water level of the floodplain and multiplied by the number of the pixels that have the same height and by the pixel size (90 x 90 m). Thereafter, it was possible to calculate the water volume for the floodplain by summing up these values, to obtain the aggregated amount in cubic meters. That value was considered representative for that month of the satellite image.

Additionally, satellite images of April for each year (2000-2011) were used to determine the frequency of flooding in each polygon, based on the observation of the MNDWI in the satellite image. This information, together with the volume calculated, was used to compare the occurrence of flooding in the different polygons over time.

4.4 Assessment of Environmental Flow in the Caprivi Region.

There are four main types of environmental flow assessment approach**: hydrological, hydraulic rating, habitat rating and holistic methods** (*Tharme*, 1996).

The earliest, **hydrological methods** are based solely on hydrological data. They are essentially desktop methods that use summary statistics of flow, derived from historical flow data and are used to estimate the environmental flow without ecological data. Environmental flow is usually given as a percentage of average annual flow or as a percentile from the duration flow curve, on an annual, seasonal or monthly basis.

Two of the most well know methods are Tennant Method (Tennant, 1976) and the Range of Variability Approach (Richter, 1997); both developed in the USA.

Hydraulic rating methods are based on historical flow records and cross-section data in critically limiting biotopes. Environmental flow is given as a discharge that represents optimal minimum flow below which habitat is rapidly lost, and for its calculation the model assume links between hydraulics (wetter perimeter, depth, velocity) and habitat availability of target biota. They use hydraulic as a surrogate for the biota.

The most common method is the Wetted Perimeter (Reiser et al., 1989).

Habitat rating methods are widely used and based on hydrological, hydraulic and biological response data. The model links between discharge, available habitat conditions and their suitability to target biota. Environmental flows are proposed or evaluated upon several scenarios, based on habitat-discharge curves or habitat time series and exceedence curves of habitat indices, e.g. the weighted usable area (WUA).

The most common method is PHABSIM (Physical Habitat Simulation Model, Milhous, 1989).

Holistic methodologies are actually frameworks that incorporate hydrological, hydraulic and habitat simulation models. They are the only methodologies that adopt a holistic, ecosystem-based approach to environmental flow determinations. The purpose of these methodologies is to maintain or restore the flow-related biophysical components and ecological processes of in-stream and groundwater system, floodplains and downstream receiving water. Holistic methodologies aim to address the water requirement of the entire "riverine ecosystem" (Arthington et al. 1992).

Holistic Methodologies were predominantly developed and used in South Africa and Australia, but recently such methods have begun to attract interest in other regions of the world, with strong expressions in Europe, Latin America, Asia and Africa (Tharme, 2003).
Some of them are, The South African Building Block Methodology or BBM (King and Tharme 1994; King and Louw 1998; King *et al.* 2002), which was the first structured approach of this type, the Benchmarking Methodology (Brizga *et al.* 2001) or the Downstream Response to Imposed Flow Transformation (DRIFTT) (King et al. 2003; Arthington *et al.* 2003a), developed in South Africa which is one of the most recent.

In the most recent review of international environmental flow assessment, *Tharme* (2003) recorded 207 different methods within 44 countries. Several different categorizations of these methods exist, three of which are shown in the table below.

Table 5: Methods to determine environmental flows
Source: Global Environmental Flow Network (eFlowNet)

Organisation	**Categorization of methods**	**Sub-category**	**Example**
UICN (Dyson et al., 2003)	Methods	Look-up table	Hydrological (e.g.Q95 Index) Ecological (e.g. Tennant Method)
		Desk-top analyses	Hydrological (e.g. Richter method) Hydraulic (e.g. Wetter Perimeter Method) Ecology
		Functional Analyses	BBM, Expert panel assessment Method, benchmarking Method
		Habitat modeling	PHABSIM
	Approach		Expert Team approach Stakeholder Approach (expert and no expert)
	Framework		IFIM, DRIFT
World Bank (Brown & King, 2003)	Prescriptive Approaches	Hydrological Index Methods	Tennant method
		Hydraulic rating Methods	Wetter Perimeter Method
		Expert Panel	
		Holistic Approach	BBM
	Iterative Approach		IFIM DRIFT
IWMI (Tarme, 2003)	Hydrological Index Method		Tennant Method
	Hydraulic Rating Methods		Wetter perimeter method
	Hábitat Simulation Methodologies		IFIM
	Holistic Methodologies		BBM DRIFT Expert Pannel Benchmarking Methodology

Table 6: Examples of some methods, components used and references.

Methodology type	Example Method	Method Input	Components	References
Standard Setting or Hydrological Method	Tennant method	Average annual flow	Width, Depth, Velocity, Substrate & Side channels, Bars & Islands, Cover, Migration, Temperature, Invertebrates, Fishing & Floating, Esthetics & Natural beauty	Tennant D.L., 1975
Transect of Hydraulic Rating Methods	Wetted Perimeter Method	Cross section coordinates (x,y) and slope (with use of a cross section analyzer)	Depth, Velocity and Spawning discharge.	Collins, M. 1972.
Incremental of Habitat Simulation Methods	PHABSIM	Multiple cross sections longitudinally along the stream segment with discharge and water surface level calibrations pairs	Velocity, Depth, Channel Index and Temperature.	Bovee, K. 1982

In our case of study, the environmental flows were calculated considering the data from the **Katima Mulilo** gauging site, and hydrological methods will be used for its determination. There is no significant human alteration (like dams, dykes…) upstream yet, so the historical data has not been affected for that reason.

4.4.1 Tennant Method

The "Montana Method" or "Tennant method", was introduced by Donald Tennant (1976) for determining instream flow requirements for fish. The method uses a percentage of average annual flow (AFF), to determinate fish habitat quality. It concluded that 10% of AFF is the minimum for short term fish survival (named as "poor condition"), 30% of AFF is considered to able to sustain fair survival conditions, and 60% of AFFF is excellent to outstanding habitat.

It was created using data collected on 58 cross section on 11 different streams within Montana, Nebraska and Wyoming, the three states of the USA. Tennant collected detailed cross section data that characterized different aspect of fish habitat. These included width, depth, velocity, temperature, substrate and side channel, bars and islands, cover, migration, invertebrates, fishing and floating, and esthetic and natural beauty. With these data, a relationship between the average flow and the flow requirement was established, in order to maintain the fish habitat qualities. Traditionally it was considered as a hydrological method because its application is based on the calculation of fixed flows, but actually it is a hydraulic method which takes into account the relationship between the flow and hydraulic parameters as the depth, the water velocity, the width of the water body, etc. (Martinez Capel, F., Bardina, M., Cirera,J., Munné, A., Muñoz-Mas,R. Comparasion of Hydrologic Methods for mínimum Environmental Flow Assessment and Phisical Habitat Simulatios in Catalonian Basins (NE Spain). *7th International Symposium on Ecohydraulics. Proceedings of the 7th International Symposium Ecohydraulics*.)

In this thesis, the historical series of data from 1943-2011, excluding the years between 1955-1964 (with no available data) were used, in order to apply this method.

Firstly, the mean yearly flow was calculated. Therefore, the following percentages were calculated in order to establish an environmental flow based on the recommended base flow regimes explained in the table below. In this work, the wet season covers the months January-June, and the dry season from July to December.

Table 7: Percentages to establish a monthly environmental flow.
Source: Tennant Method (1976)

Description of flows	Recommended base flow regimes [m³/s]	
	January-June*	**July-December***
Flushing or maximum	200% of the average flow	
Optimum range	60-100% of the average flow	
Outstanding	60%	40%
Excellent	50%	30%
Good	40%	20%
Fair o Degrading	30%	10%
Poor or Minimum	10%	10%
Severe degradation	10% of average flow to zero flow	

**The wet season covers the months January-June, and the dry season from July to December. All the data are in m^3/s.*

Generally, it is asserted that ten percent of the average flow is the minimum instantaneous flow recommended to sustain short-term survival habitat for most aquatic life forms. Thirty percent is recommended as a base flow to sustain good survival conditions for most aquatic life forms and general recreation. Finally, sixty percent provides excellent to outstanding habitat for most aquatic life forms during their primary periods of growth and for the majority of recreational uses.

In this Master Thesis, the Tennant Method was adapted in order to obtain a minimum monthly flow considering the “Good” and “Fair o degrading” conditions. It was done because of the low variability of this method.

4.4.2 Percentile 90, 95 (Q347 and Q330)

This is a statistic method that evaluates a certain flow which is equal or exceeded 90% of the year, or in daily terms 328.5 days. The same for the percentile 95 (evaluates the flow exceeded 95% of the years, 346.75 days).

Based on the available daily data, the duration curves for each month have been calculated. After that, the values which correspond with the 90% and 95% were used to establish a minimum monthly environmental flow.

In the Chapter 5, results, the values of the monthly environmental flow are given, as well as the duration curve for each month.

4.4.3 Range of Variability Approach (RVA).

This approach derives from the aquatic ecology theory in which the hydrological variability has a critical role, and it associated characteristics of timing, frequency, duration and rates of change, in sustaining the ecosystems diversity.

It is usually applied on rivers where the conservation of native aquatic biodiversity and the protection of natural ecosystem functions are the main objectives. This method incorporates the concepts of hydrological variability and river ecosystem integrity.

The RVA Method begins with a comprehensive characterization of ecologically relevant attributes of a flow regime and then translates these attributes into more simple, flow-based management targets. These targets are used as guidelines for designing a water management system and water management rules capable of attaining the flow conditions.

The RVA helps to identify annual river management targets, based upon a comprehensive statistical characterization of relevant flow regime characteristics (Richter et al., 1996). It has six steps for setting, implementing and define the specific aims for the river managements, which are going to be explained briefly:

Step 1:

The natural range of streamflow variation is characterized using thirty-two ecologically relevant parameters using the *Indicators of Hydrologic Alteration* (IHA), method of Ritcher *et al.* (1996). For that, should exist long term (>20 years) daily streamflow. These parameters are list in the table below. In this case study, the analyses are based on monthly data of stream flow, because this is the time scale used in the generation of data scenarios, which were produced in specific tools for water resources management in the University of Hannover. Therefore, only those parameters of the RVA based on monthly river flow data were considered in this study, in order to obtain robust results based on monthly river flow data.

Table 8. Indicators of hydrological alteration (Richter, *et al*. 1996).
(*). Only these parameters were calculated, in order to obtain robust results (based on monthly river flow data)

IHA STADISTICS GROUP	REGIME CHARACTERISTICS	HYDROLOGICAL PARAMETERS
Group 1: Magnitude of monthly water conditions	Magnitude Timing	Mean value for each calendar month (*)
Group 2: Magnitude and duration of annual extreme water conditions	Magnitude Duration	Annual minima 1-day means
		Annual maxima 1-day means
		Annual minima 3-day means
		Annual maxima 3-day means
		Annual minima 7-day means
		Annual maxima 7-day means
		Annual minima 30-day means
		Annual maxima 30-day means
		Annual minima 90-day means
		Annual maxima 90-day means
Group 3: Timing of Annual Extreme Water Conditions	Timing	Julian date of each annual 1-day maximum
		Julian date of each annual 1-day minimum
Group 4: Frequency and Duration of High/Low Pulses	Frequency Duration	No. of high pulses each year
		No. of low pulses each year
		Mean duration of high pulses within each year (days)
		Mean duration of low pulses within each year (days)
Group 5: rate/Frequency of water condition changes	Rates of change Frequency	Means of all positive differences between consecutive daily values
		Means of all negative differences between consecutive daily values
		No. of rises
		No. of falls

Step 2:

Thirty-two management targets, one for each of the thirty-two IHA parameters, are selected. The fundamental concept for the correct management of the river is that the annual value for each IHA parameter should falls within the range of natural variation for that parameter. Therefore, the management target for each parameter is expressed as a range of acceptable value. The target may have both upper and lower bounds, or only a minimum or maximum. If it is possible, the management targets should be based on available ecological information. In the absence of adequate ecological information, is recommended that the ± 1 standard deviation values be the default for setting initial targets.

Step 3:

Using the RVA targets as design guidelines, should be design a set of managements rules, or a management system, that will attain of the targeted flow conditions in most, if not all, years. Depending on the nature of the selected RVA targets, the management system might be designed to achieve targeted flow condition every year.

Step 5:

At the end of each year, actual streamflow variation is characterized using the same thirty-two hydrological parameters, and the values of these parameters are compared with the RVA target values, to see which targets were met or not met.

Step 6:

RVA targets should be developed incrementally, based on the system´s performance in meeting the RVA targets over the past of the years.

The environmental flow will be calculated based on the reference condition of the river (the parameters obtained with the software IHA, Indicators of Hydrologic Alteration), and the comparison with the same parameters under futures scenarios.

Besides the Indicators of Hydrologic Alteration, other parameters describing monthly or annual characteristics were calculated, which represent a wide range of ecologically-relevant flow statistics (Mathew and Ritcher 2007; Monk and others 2006,2007; Olden and Poff 2003; Richter and others 1996). These include indices that characterize the central tendency in flow magnitude, the magnitude of low flows, like the mean minimum monthly flows (ML, 12 parameters) and the average of minimum monthly flows and measures of high flow, such as the mean maximum monthly flow (MH, 12 parameters) and the average of maximum monthly flows. The coefficient of the variation in all the mean annual flows (i.e., 34 years in "actual conditions" and 49 in the future scenario) was calculated which represents the inter-annual variability in the flow regimes (Belmar, *et al.* 2011).

The first scenario corresponds to the resulting stream flow series after the agricultural water abstraction (from the year 2013 to 2050. Source: BGR, 2005). The second scenario is the resulting flow after the extraction for the water demands (domestic, urban and cattle water demand, from the years 2013 to 2050. Source: BGR, 2005). The third scenario, a combination of these two, will be used to obtain the IHA parameters because it is the most unfavorable scenario and because it combines two situations which are very probable to occur in the future, an increase of demand for the domestic uses and livestock together with the increase of agricultural demands. The runoff time series were created with a stochastic approach by Matthias Beyer (hydrologist from the CERPA- Team).

5 Results and discussions

5.1 Hydrological characterization of the river flow

The following graph shows the duration curve for the Katima Mulilo gauging site (considering runoff) for the series of data for 1943-2011 (excluding the years from 1955-1965 with no available data).

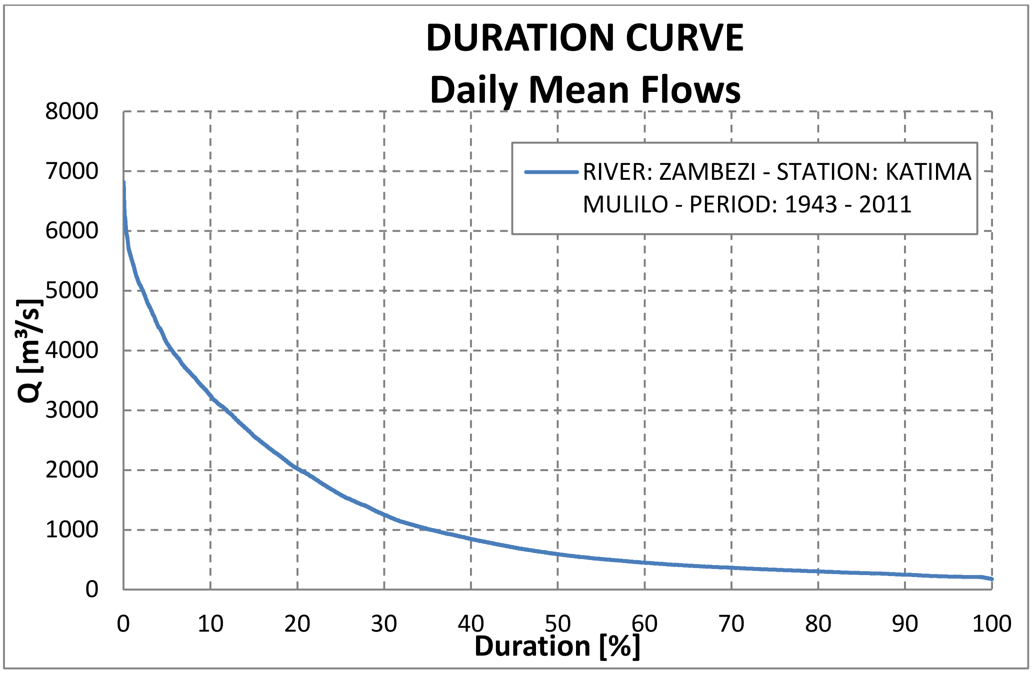

Figure 19: Flow duration curve at Katima Mulilo gauging site

The next figure shows the duration curves, after splitting data from the wet season and the dry season. Looking at these flow duration curves for Katima Mulilo, it becomes clearer how different wet and dry season are. The variability is very different, very low in the dry seasons, and very large within the months corresponding to the wet season, when all the ranges of stream flow can be found.

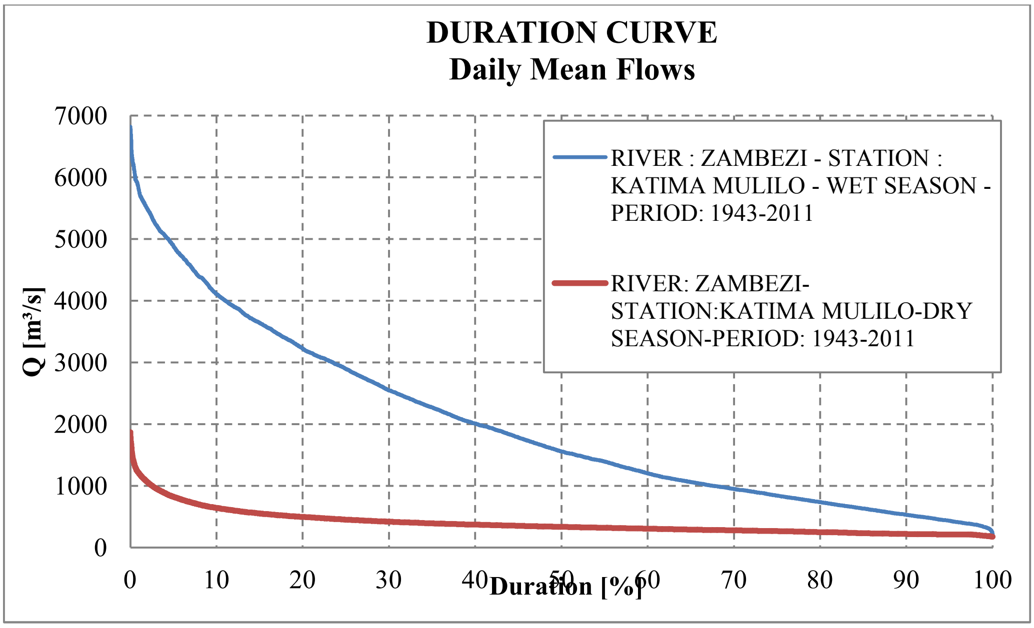

Figure 20: Flow duration curve for the wet and dry season at Katima Mulilo gauging station.
To characterize seasonality further, the following figure shows the frequency plots of mean daily flow for the dry and wet season. (Katima Mulilo gauging station. Data for the years 1943-2011, excluding from 1955 to 1965).

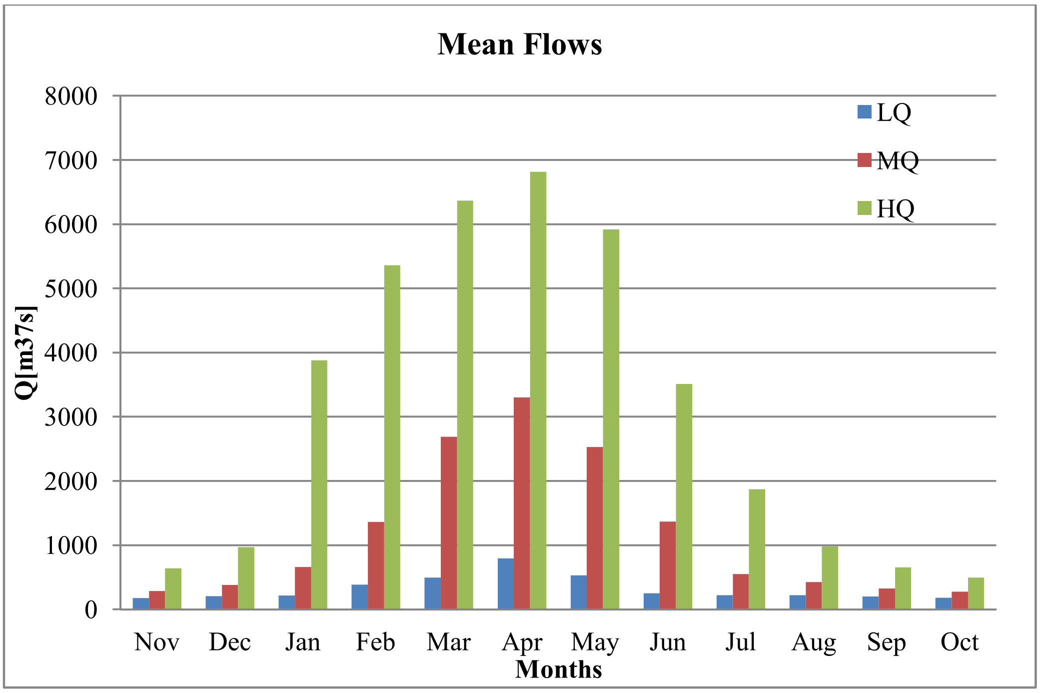

Figure 21: Mean flows (low, mean and high) at Katima Mulilo gauging station.
LQ: Lowest monthly discharge for each month for the entire period.
MQ: Mean monthly discharge for each month for the entire period.
HQ: Highest monthly discharge for each month for the entire period.

In the Chapter 4.1 it was described how a year can be classified into “extremely wet”, “wet”, “normal”, “dry” or “extremely dry” with regards to the runoff series data. The results of this classification are summarized below.

Table 9: Classified water year types for the runoff time series

Classification based on flood volume					
1943	dry year	**1974**	normal year	**1994**	dry year
1944	normal year	**1975**	wet year	**1995**	dry year
1945	normal year	**1976**	wet year	**1996**	very dry year
1946	dry year	**1977**	normal year	**1997**	dry year
1947	wet year	**1978**	very wet year	**1998**	normal year
1948	wet year	**1979**	wet year	**1999**	normal year
1949	very dry year	**1980**	wet year	**2000**	normal year
1950	wet year	**1981**	normal year	**2001**	wet year
1951	normal year	**1982**	dry year	**2002**	dry year
1952	wet year	**1983**	dry year	**2003**	normal year
1953	wet year	**1984**	dry year	**2004**	wet year
1965	normal year	**1985**	dry year	**2005**	dry year
1966	wet year	**1986**	normal year	**2006**	normal year
1967	normal year	**1987**	dry year	**2007**	wet year
1968	very wet year	**1988**	normal year	**2008**	wet year
1969	very wet year	**1989**	wet year	**2009**	very wet year
1970	wet year	**1990**	very dry year	**2010**	very wet year
1971	normal year	**1991**	normal year	**2011**	very wet year
1972	dry year	**1992**	very dry year		
1973	dry year	**1993**	normal year		

In the following graph, the seasonal pattern of each year, based on mean flows, can be observed.

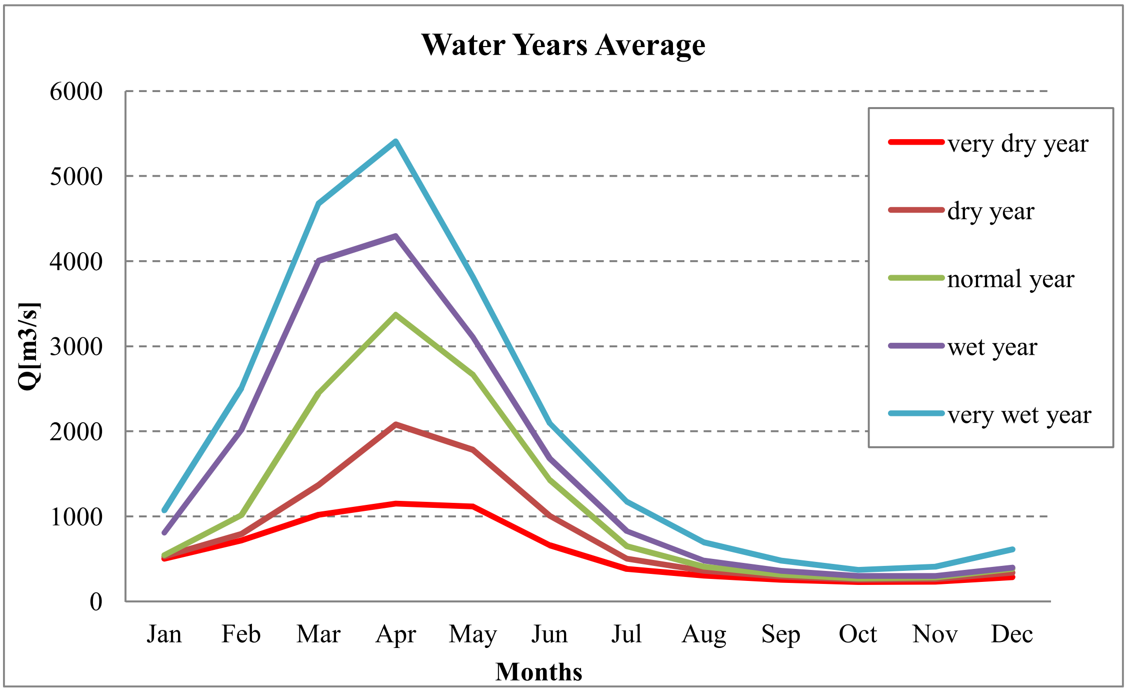

Figure 22: Seasonal pattern of each of the water year types. The line of each type of hydrological year was constructed as the mean of the stream flows at each month for all the years in each type.

From the table, the high inter-annual variability and periodical behavior of river flow can be easily identified. Most of the years are considered as "dry", "normal" or "wet" years. The types "Very dry" and "very wet" years occur only in a low proportion (in total, "very dry" occurs 7% of the years and "very wet", 10% of the years). There is a notable concentration of "very wet years" among the recent years. These years with extreme flooding activate the Bukalo channel filling the Lake Liambezi. The reason for that is not yet clear, but there are various possible scenarios that caused recent big floods, such as (Source: Beyer et al., 2013. CERPA project):

- Strong rains upstream; change of the rainfall characteristic
- Increase direct runoff due to a trend of change in the land use within the watershed
- The previous year's groundwater recharge rate in combination with flood favoring rainfall characteristics
- The combination of these reasons

To investigate such relationship can be very useful for future works and predictions. There is very little information about this topic. Until now, it is assumed that a combination of the state of the aquifer in combination with flood favoring rainfall characteristics cause massive flooding. In that way, the previous year affects the probability of flooding in the next one.
In the following graph, the differences of the flows during the wet and the dry seasons can be observed. The mean monthly flow is also included as a reference.

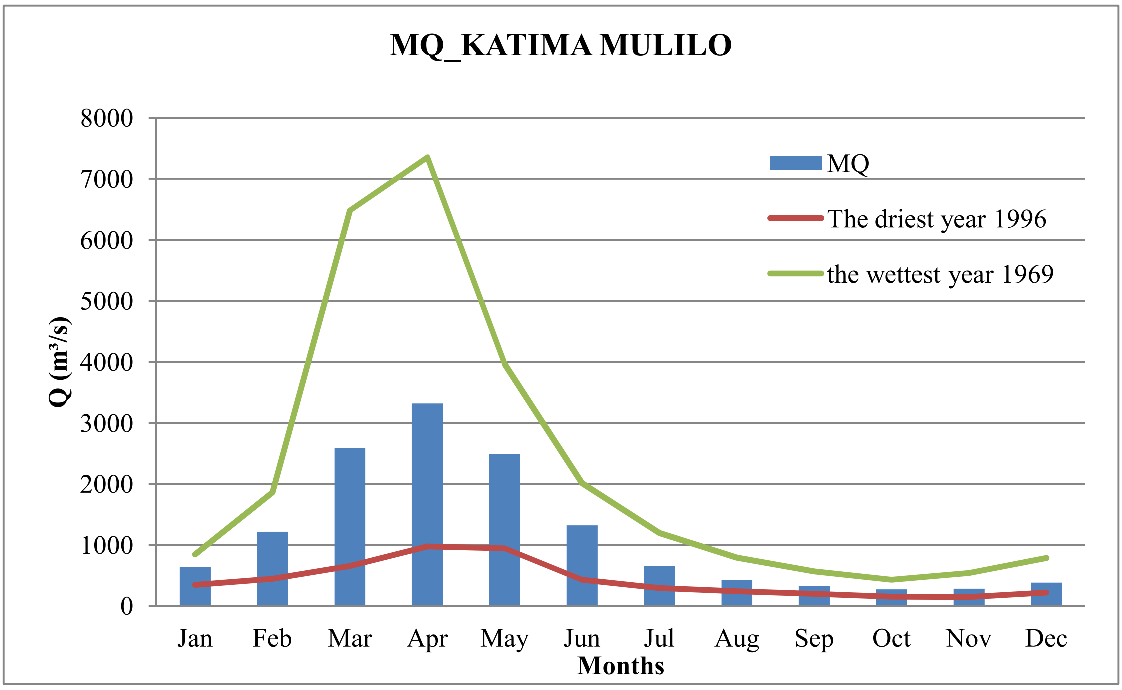

Figure 23: Mean monthly flow for the whole dataset (MQ) at Katima Mulilo gauging site, in comparison with the mean monthly flow during the driest (1996) and the wettest year (1969).

Concerning precipitation, the criteria for the classification of the years was explained before, in the chapter 4.1. The results are summarized in the table below:

Table 10: Classification of the water years based on precipitation criteria

Classification based on precipitation criteria					
1943	Wet year	**1974**	Wet year	**1994**	Dry year
1944	Wet year	**1975**	Wet year	**1995**	Dry year
1945	Dry year	**1976**	Wet year	**1996**	Dry year
1946	Wet year	**1977**	Wet year	**1997**	Wet year
1947	Dry year	**1978**	Wet year	**1998**	Wet year
1948	Wet year	**1979**	Dry year	**1999**	Wet year
1949	Wet year	**1980**	Wet year	**2000**	Wet year
1950	Wet year	**1981**	Wet year	**2001**	Wet year
1951	Wet year	**1982**	Dry year	**2002**	Dry year
1952	Wet year	**1983**	Dry year	**2003**	Dry year
1953	Wet year	**1984**	Dry year	**2004**	Wet year
1965	Dry year	**1985**	Wet year	**2005**	Dry year
1966	Wet year	**1986**	Wet year	**2006**	Wet year
1967	Wet year	**1987**	Dry year	**2007**	Wet year
1968	Wet year	**1988**	Wet year	**2008**	Wet year
1969	Wet year	**1989**	Wet year	**2009**	Wet year
1970	Dry year	**1990**	Dry year	**2010**	No data
1971	Wet year	**1991**	Dry year	**2011**	No data
1972	Wet year	**1992**	Wet year		
1973	Dry year	**1993**	Wet year		

Depending on the data considered (runoff or rainfall) the classification of the years will be different as can be noticed in these results. Runoff is not only defined by the total annual rainfall, but other parameters are relevant, such as the infiltration and runoff coefficient, rainfall spatial and temporal distribution, groundwater levels, etc. One year could be dry in terms of runoff, but could be wet based on precipitation criteria and vice versa.

A temporal analysis of the precipitation, in the form of duration curve, was performed as shown in the following graph.

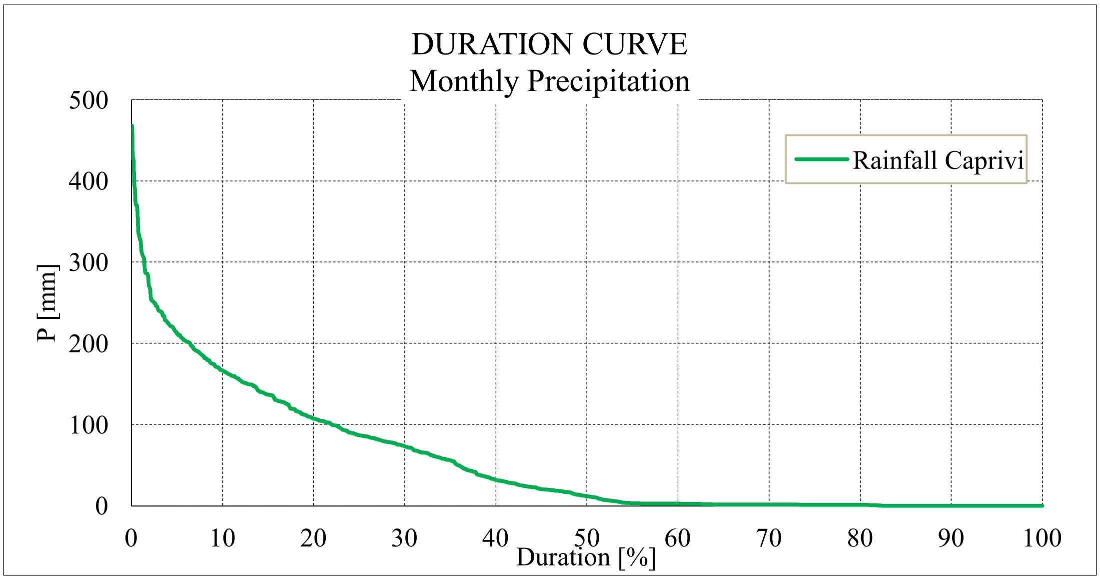

Figure 24: Duration curve for precipitation. Time series from 1943 to 2010. Rainfall station: Katima Mulilo

As shown in figure 24, in nearly half of the months there is no rainfall at all, i.e. during the dry season. The other months represent the wet season. In the rainy period, 40 percent of the months are characterized by an amount of rainfall between 20 and 200 mm, whereas the remaining months are considered to be extreme, with a rainfall higher than 200 mm. The yearly rainfall in Caprivi is around 600-700 mm/year that is almost one third of the overall precipitation registered at the Katima Mulilo gauging station.

The recurrence interval (in years) of the maximum annual flow (m^3/s) was calculated and the following results were obtained, in the next table.

Table 11: Analysis of the recurrence interval (in years) of the maximum annual flow (m^3/s), based on 34 years, from 1965 to 1999.

year	1-day max (annual max)	Julian date of ocurrence	Ranking of Max flow	Recurrence period (T)	Probability the value can be equalled or exceeded
1969	6817	100	1	**36.0**	0.03
1978	6251	114	2	18.0	0.06
1979	5675	111	3	12.0	0.08
1976	5568	98	4	9.0	0.11
1975	5409	99	5	7.2	0.14
1968	5312	98	6	6.0	0.17
1966	5276	95	7	5.1	0.19
1970	5132	78	8	4.5	0.22
1993	4532	117	9	4.0	0.25
1989	4386	125	10	3.6	0.28
1998	4350	96	11	3.3	0.31
1981	4146	120	12	3.0	0.33
1999	4110	120	13	2.8	0.36
1986	4107	114	14	2.6	0.39
1967	4011	117	15	2.4	0.42
1980	3774	102	16	2.3	0.44
1971	3714	86	17	2.1	0.47
1988	3498	109	18	2.0	0.50
1977	3457	133	19	1.9	0.53
1974	3254	72	20	1.8	0.56
1965	3171	80	21	1.7	0.58
1991	3075	78	22	1.6	0.61
1987	2986	92	23	1.6	0.64
1994	2772	89	24	1.5	0.67
1985	2561	128	25	1.4	0.69
1984	2507	93	26	1.4	0.72
1972	2501	124	27	1.3	0.75
1995	2092	98	28	1.3	0.78
1997	2085	126	29	1.2	0.81
1982	2016	107	30	1.2	0.83
1973	1729	119	31	1.2	0.86
1983	1497	86	32	1.1	0.89
1990	1308	145	33	1.1	0.92
1996	1137	124	34	1.1	0.94

1992	1111	91	35	**1.0**	0.97

Down here it is shown the plot relating the recurrence interval (years, in logarithmic scale) with the maximum annual flow (m3/s). The linear relation was not shown in the plot, because of the low coefficient of regression obtained (r2<0.45). The results indicated that the mean of the date when the maximum annual flow occurs corresponds with 105, which means 15th of April.

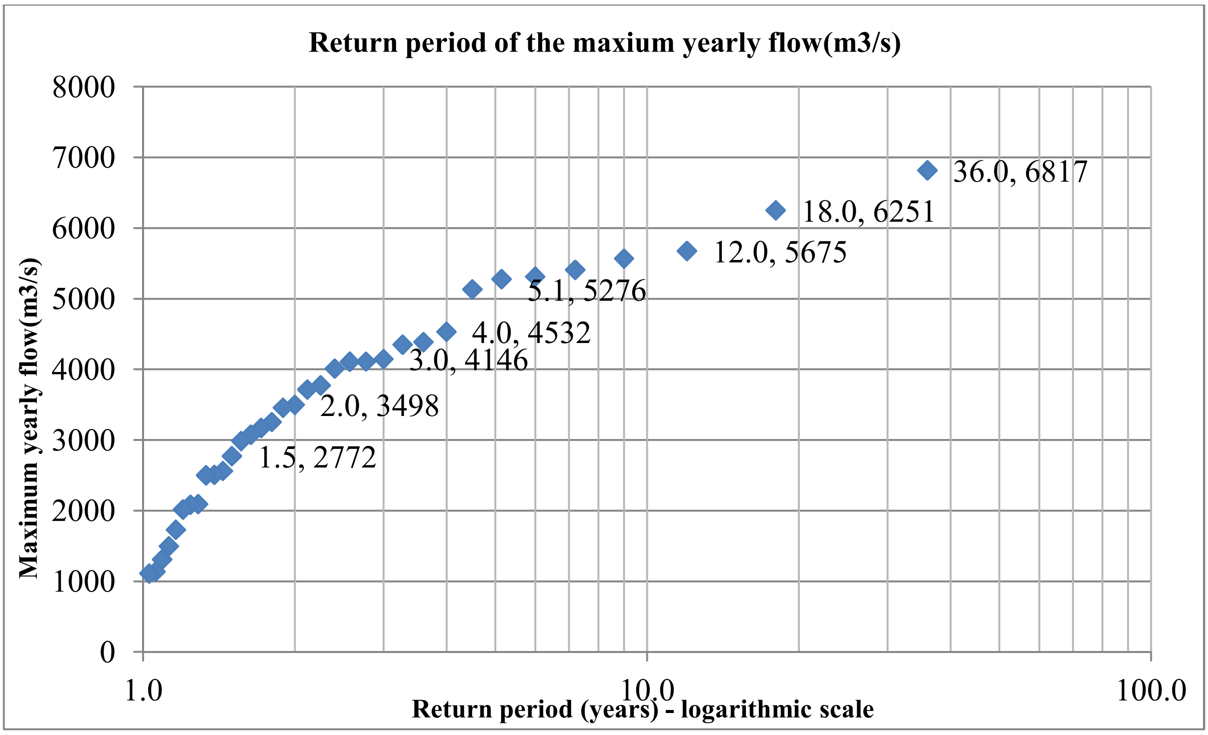

Figure 25: Plot relating the recurrence interval (years, in logarithmic scale) with the maximum annual flow (m^3/s) based on the gauging site of Katima Mulilo, during the period 1965-1999. Some relevant data are tagged, i.e. the maximum annual flows related to the recurrence interval of 1.5, 2, 3, 4, 5.1, 12, 18 and 36 years.

The recurrence interval for the highest flow recorded (6817 m^3/s), based on the historical data series from 1965 to 1999, was 36 years. That is, on average this maximum annual flow can be equalled or exceeded every 36 years. However, this was the maximum flow recorded, in 36 years, thus it is possible that longer time series could give different results with a larger temporal perspective.

5.2 Determination of the mulapos using remote sensing techniques

The determination of the mulapos by the use of remote sensing comprises a major part of the effort in investigation of the present Master Thesis. In this chapter, the results of the mapping are presented. Later on, a comparative assessment of the different flooding periods (during the year 2000-2011) is shown.

The following picture shows the MNDWI index for May 2008. The mulapos correspond with the area in blue, as they are the lowest areas in the floodplain that still remain flooded in the month of May.

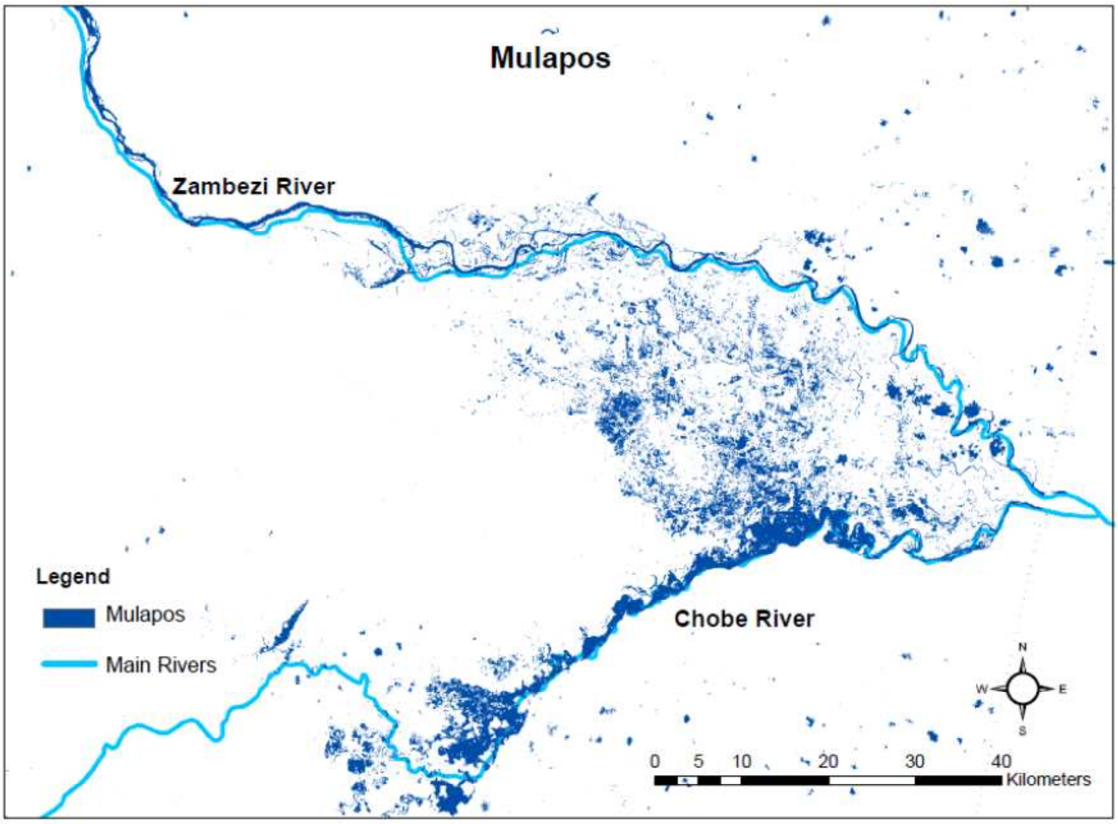

Figure 26: Mulapos in the Caprivi-Chobe wetland. The lighter blue line corresponds with the Chobe and Zambezi rivers. The darker corresponds with the location of the mulapos.

The total water volume (for the mulapos) is 150400800 m^3 that is 150.4 hm^3. As a reference, can be used the following data: the Serena reservoir, the biggest one in Spain, has a total capacity of 3219 hm^3, and the Tous reservoir has a total capacity of 378.60 hm^3

5.2.1 Comparative assessment of the different flooding during the years 2000-2011.

The water volume in the floodplain for each year corresponds with the following value for each year:

Table 12: Water volume in the floodplain (m^3)

Years	Volume (m^3)	Volume (Hm^3)	Mean April flow (m^3/s)
April, 2000	1161807300	1161.80	3720.12
April, 2001	2298763800	2298.76	3869.03
April, 2002	547632900	547.63	2041.11
April, 2003	2391063300	2391.06	3589.02
March, 2004	917916300	917.91	4869.99
April, 2005	555919200	555.91	1460.22
April, 2006	1061472600	1061.47	3230.03
April, 2007	1574826300	1574.82	3774.40
April, 2008	1170020700	1170.02	3659.22
April, 2009	1863664200	1863.66	5246.53
April, 2010	1395905400	1395.90	5132.48
April, 2011	1313325900	1313.32	4947.58

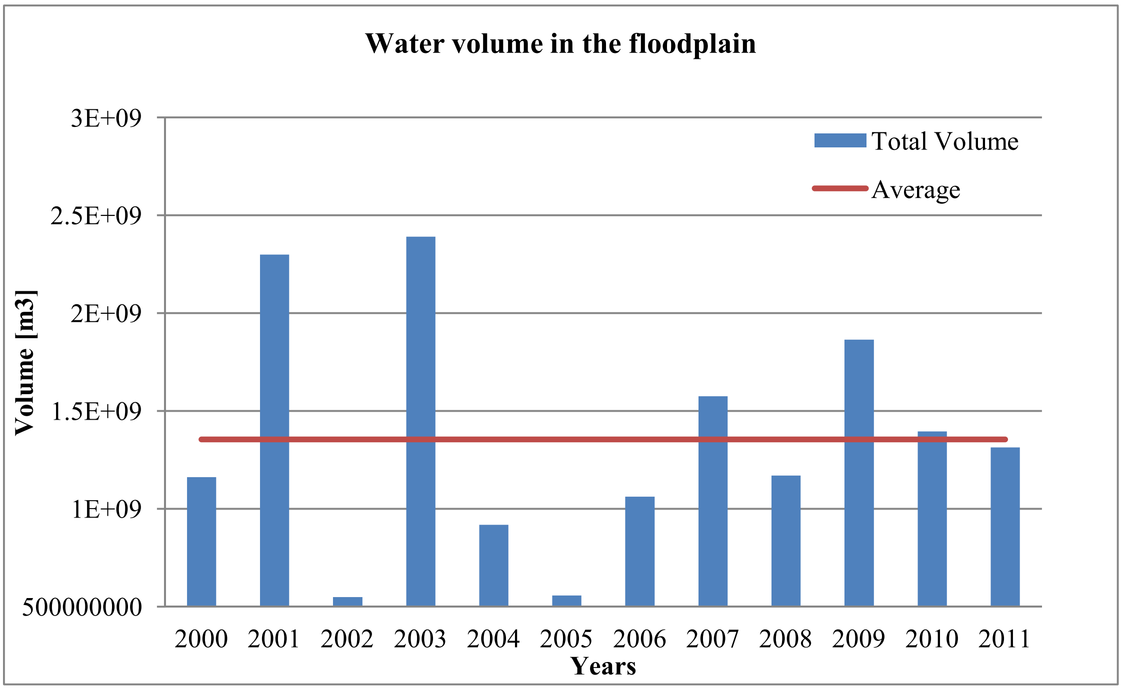

Figure 27: Water volume in the floodplain.

As shown in the figure 27, the volume calculated for the floodplain for the years 2002 and 2005 is lower in comparison with the others years.

2002 was a dry year in terms of runoff and rainfall. 2005 is considered as a very dry year in terms of runoff and as a dry year in terms of precipitation. This image has white stripes due to a sensor default in the satellite obtaining an even lower water volume (there is not any other image available for 2005).

The water volume for 2004 is also low. In 2004, the image for March was used because there isn´t any other image available for other month. 2004 is considered as a wet year (in terms of runoff and rainfall) but the water volume value is affected by a big dark cloud located just in the middle of the floodplain. Should also be considered that for 2004 the month of March was used for the calculation instead of April, which is the wettest month.

The years 2001 and 2003 have the biggest flooding. 2001 is considered as a wet year in terms of runoff and precipitation but 2003 is considered as a normal year in terms of runoff and as a dry year in terms of precipitation.

These results are corresponding with the analysis of satellite images from a specific day in every one of the year studied. Therefore, the amount of water in the floodplain is not consistent with the nature of the years in terms of runoff or rainfall. To obtain more accurate results, more than one satellite image should be studied and the average of the water volume for each should be established.

The study of the water volume in the floodplain linked with the nature of the years in terms of runoff and rainfall and climatic change scenarios could be an interested research topic. The literature about it is very little.

In the followings lines, the frequency of flooding in each polygon for each year will be presented. It was done based on the visual information from the MNDWI index for each year. The meaning of the expressions used is explained bellow.

Completely flooded: The polygon is completely covered by water.

Flooded: The polygon is very flooded but not completely covered.

Little flooded: Only the river and some mulapos are flooded.

Very little flooded: Very little water.

Sector 1.

Years	
2000	Flooded
2001	Completely flooded.
2002	Completely flooded
2003	Completely flooded
2004	Flooded
2005	Completely flooded
2006	Completely flooded
2007	Completely flooded
2008	Flooded
2009	Flooded
2010	Flooded
2011	Little flooded
Numbers of years flooded	11
Total number of years	12

Sector 2:

Years	
2000	Completely flooded
2001	Completely flooded.
2002	Completely flooded.
2003	Completely flooded.
2004	Completely flooded.
2005	Completely flooded.
2006	Completely flooded.
2007	Completely flooded
2008	Flooded.
2009	Flooded.
2010	Flooded.
2011	Flooded.
Numbers of years flooded	12
Numbers of years flooded	12

Sector 3:

Years	
2000	Completely flooded
2001	Completely flooded.
2002	Completely flooded.
2003	Completely flooded.
2004	Flooded.
2005	Completely flooded.
2006	Completely flooded.
2007	Completely flooded
2008	Completely flooded.
2009	Completely flooded.
2010	Flooded.
2011	Flooded.
Numbers of years flooded	12
Numbers of years flooded	12

Sector 4:

Years	
2000	Completely flooded
2001	Completely flooded.
2002	Flooded.
2003	Completely flooded.
2004	Completely flooded.
2005	Flooded.
2006	Completely flooded.
2007	Completely flooded
2008	Completely flooded.
2009	Completely flooded.
2010	Completely flooded.
2011	Completely flooded.
Numbers of years flooded	12
Numbers of years flooded	12

Sector 5:

Years	
2000	Completely flooded
2001	Completely flooded.
2002	Flooded.
2003	Completely flooded.
2004	Flooded.
2005	Flooded.
2006	Flooded.
2007	Completely flooded
2008	Completely flooded.
2009	Completely flooded.
2010	Completely flooded.
2011	Completely flooded.
Numbers of years flooded	12
Numbers of years flooded	12

Sector 6:

Years	
2000	Completely flooded
2001	Completely flooded.
2002	Completely flooded.
2003	Completely flooded.
2004	Flooded.
2005	Completely flooded.
2006	Completely flooded.
2007	Completely flooded
2008	Completely flooded.
2009	Completely flooded.
2010	Completely flooded.
2011	Completely flooded.
Numbers of years flooded	12
Numbers of years flooded	12

Sector 7:

There are no mulapos in sector 7.

Sector 8:

Years	
2000	No flooded
2001	Completely flooded.
2002	No flooded.
2003	Completely flooded.
2004	Very little flooded.
2005	No flooded.
2006	No flooded.
2007	Completely flooded
2008	Completely flooded.
2009	Completely flooded.
2010	Completely flooded.
2011	Completely flooded.
Numbers of years flooded	7
Numbers of years flooded	12

Sector 9:

Years	
2000	Very little flooded
2001	Completely flooded.
2002	Little flooded.
2003	Completely flooded.
2004	Little flooded.
2005	Little flooded.
2006	Flooded.
2007	Completely flooded
2008	Completely flooded.
2009	Completely flooded.
2010	Completely flooded.
2011	Completely flooded.
Numbers of years flooded	8
Numbers of years flooded	12

Sector 11:

Years	
2000	Little flooded
2001	Completely flooded.
2002	Completely flooded.
2003	Completely flooded.
2004	Flooded.
2005	Flooded.
2006	Completely flooded.
2007	Completely flooded
2008	Completely flooded.
2009	Completely flooded.
2010	Flooded.
2011	Completely flooded.
Numbers of years flooded	11
Numbers of years flooded	12

Sector 10:

Years	
2000	Very little flooded
2001	Completely flooded.
2002	Little flooded.
2003	Completely flooded.
2004	Little flooded.
2005	Little flooded.
2006	Little flooded.
2007	Completely flooded
2008	Completely flooded.
2009	Completely flooded.
2010	Completely flooded.
2011	Completely flooded.
Numbers of years flooded	7
Numbers of years flooded	12

Sector 12:

Years	
2000	Flooded
2001	Completely flooded.
2002	Completely flooded.
2003	Completely flooded.
2004	Flooded.
2005	Completely flooded.
2006	Completely flooded.
2007	Completely flooded
2008	Completely flooded.
2009	Completely flooded.
2010	Completely flooded.
2011	Completely flooded.
Numbers of years flooded	12
Numbers of years flooded	12

5.2.2 Maps with the flooding for each of the years studied

The images used come from the satellites Landsat 5 and Landsat 7. The images that correspond to the year 2005, 2006 and 2007 (Landsat 7) have white stripes, due to a sensor default "Scan Line Corrector SLC" which stopped working in May 2003. There are no other images available for April for these years, so these last were used.

In March 2004, there is a big cloud over the floodplain so the calculations are not very accurate. There are no any other images available for this year.

The following maps were elaborated by the author of this thesis.

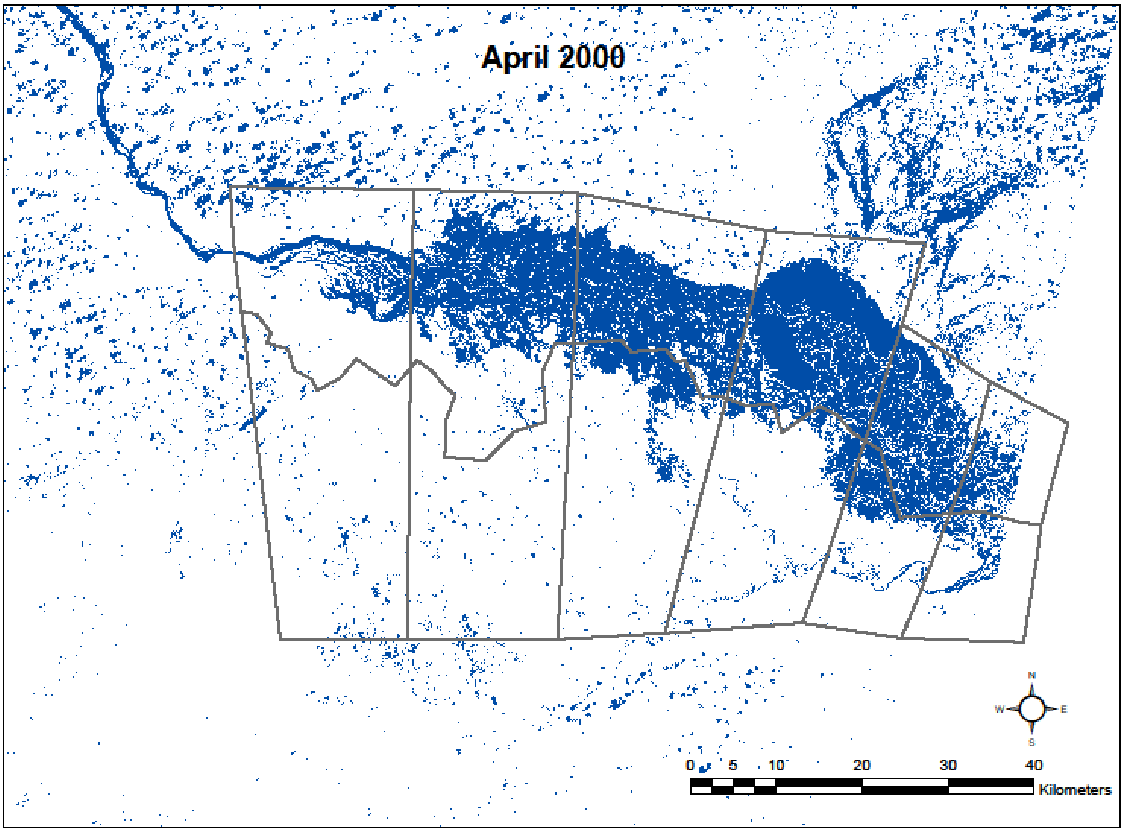

Figure 28: mndwi index for April 2000

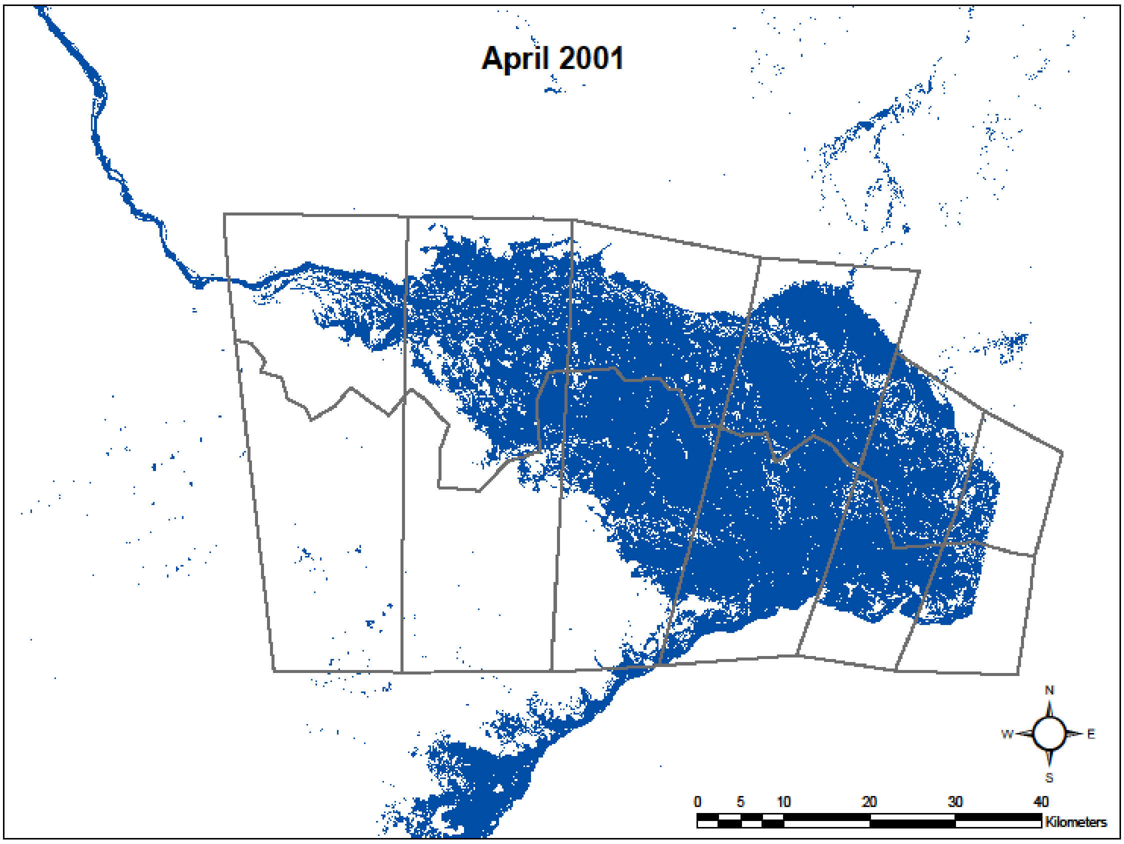

Figure 29: mndwi index for April 2001

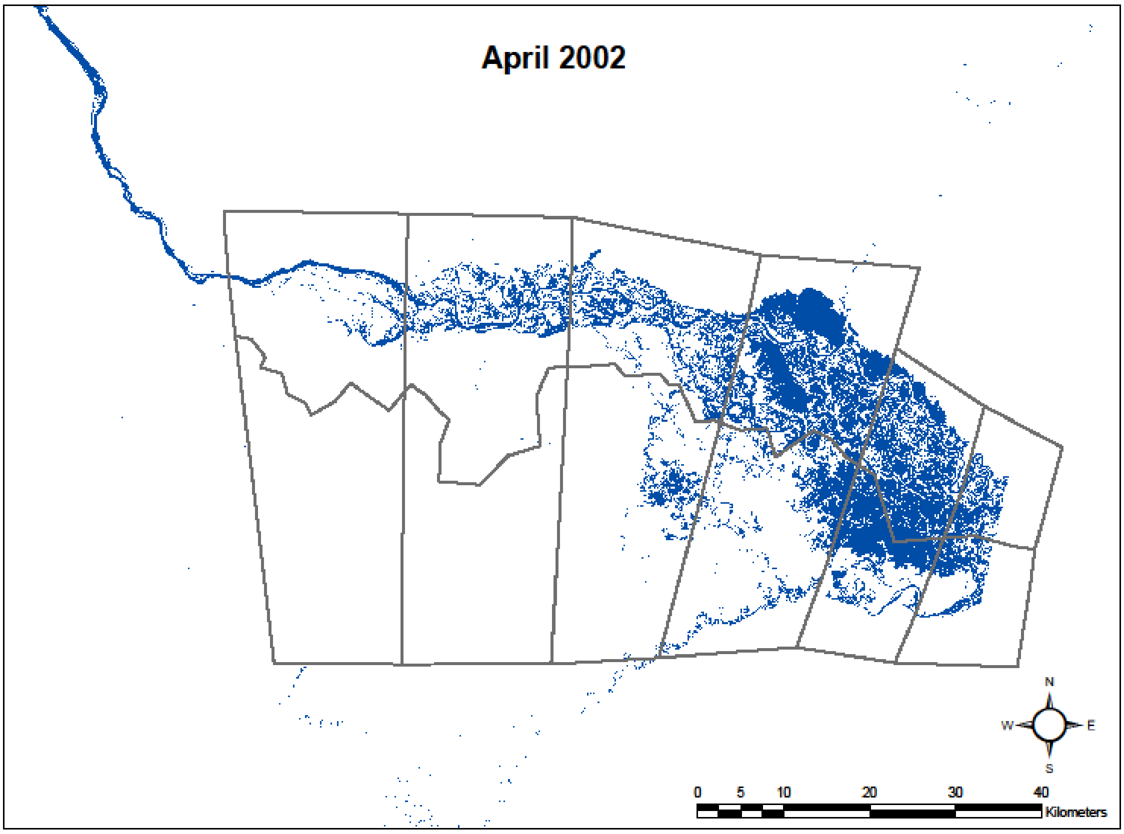

Figure 30: mndwi index for April 2002

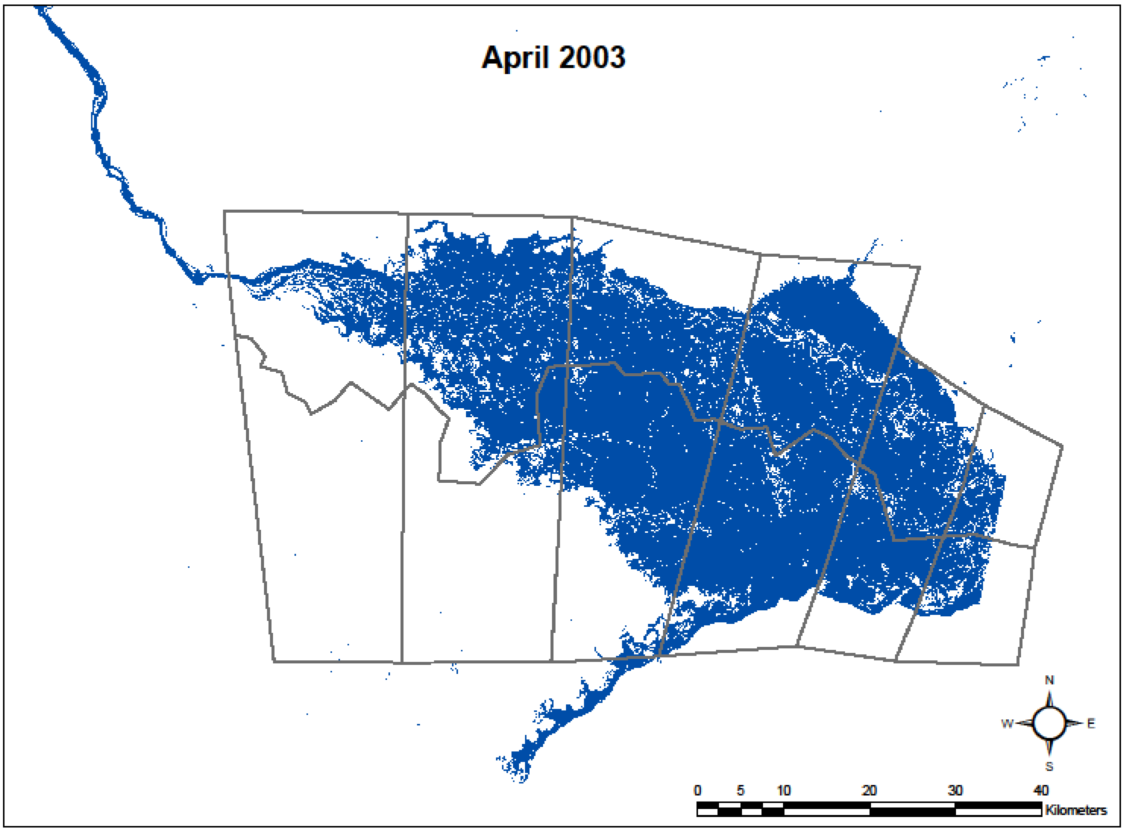

Figure 31: mndwi index for April 2003

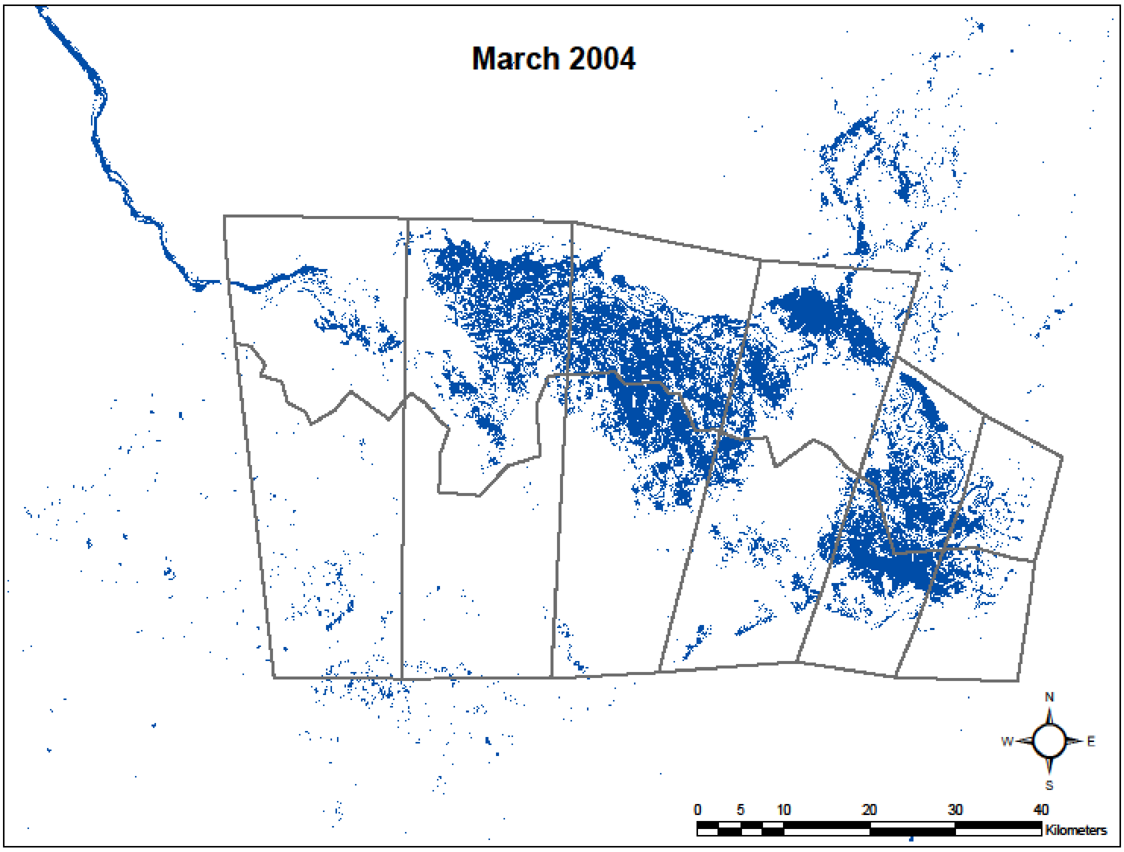

Figure 32: mndwi index for March 2004

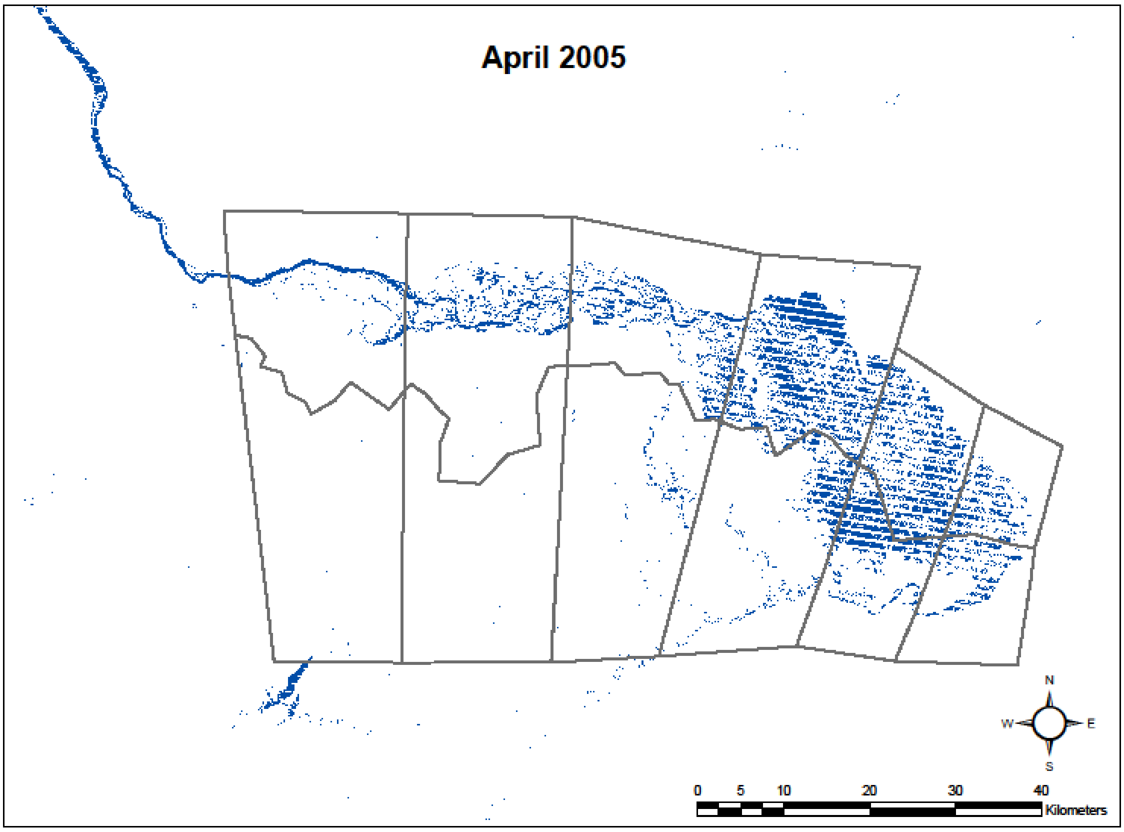

Figure 33: mndwi index for April 2005

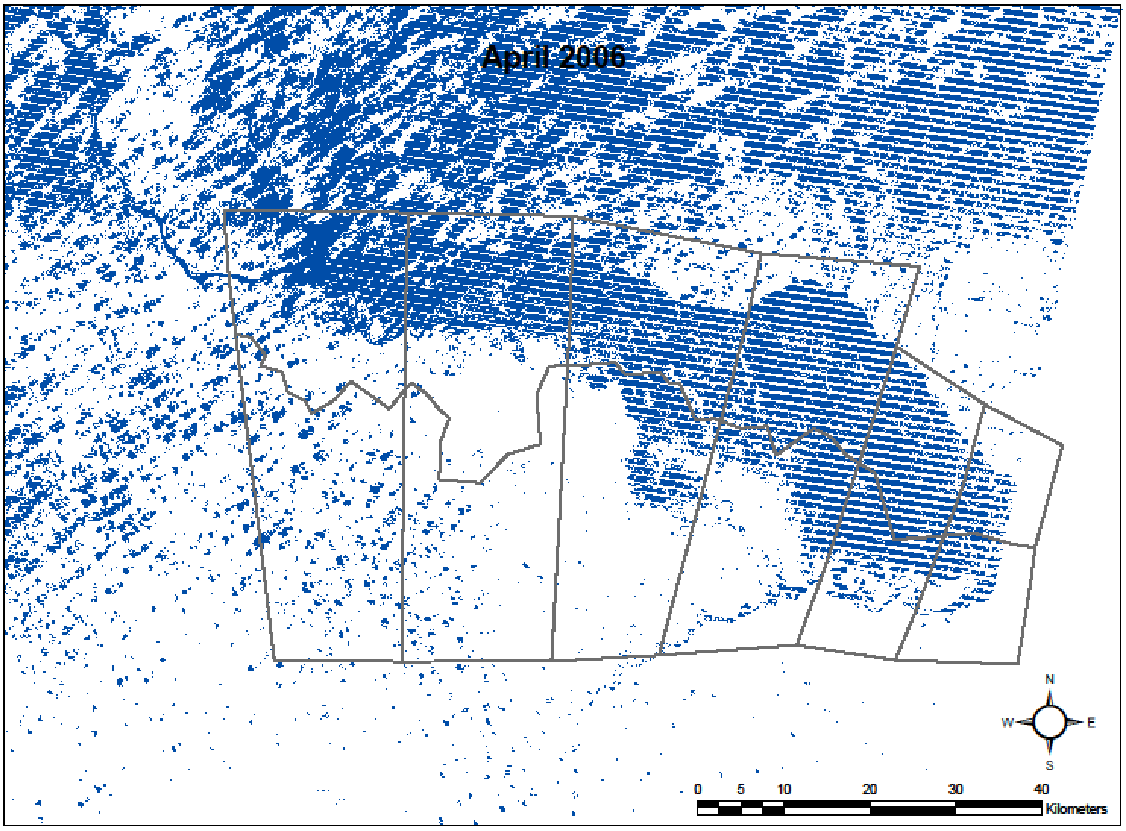

Figure 34: mndwi index for April 2006

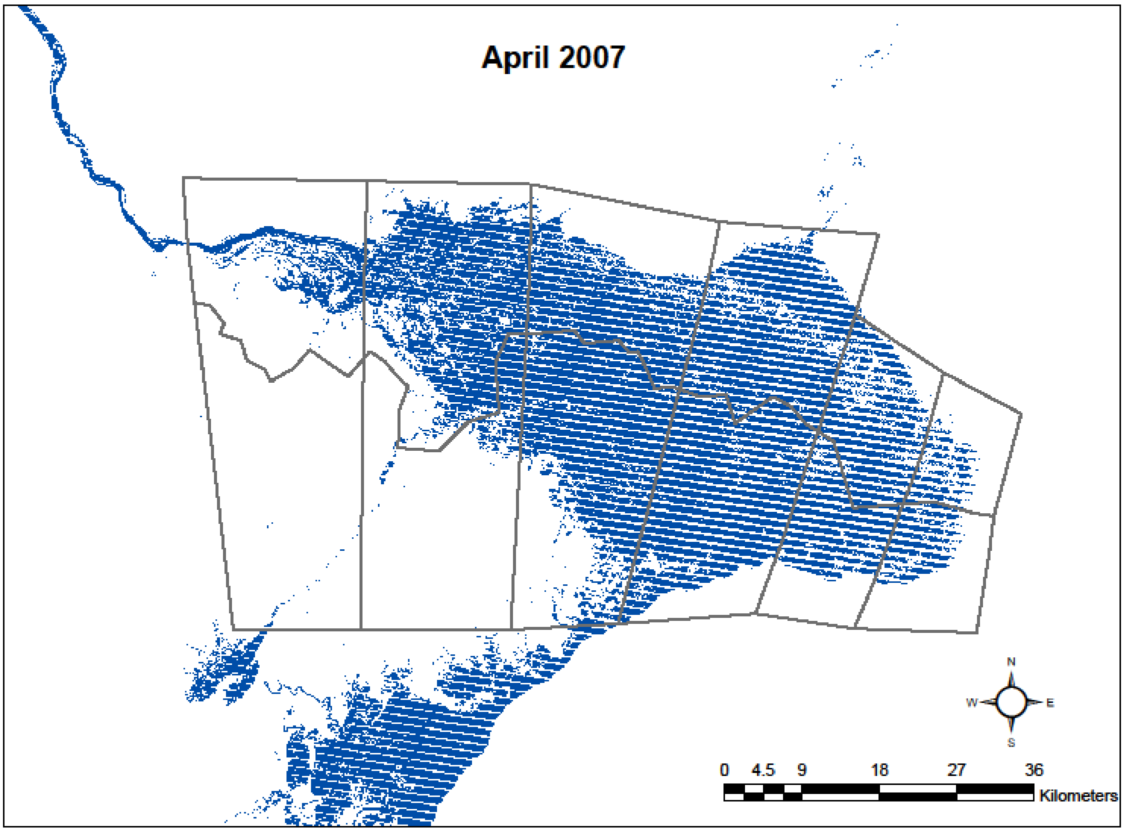

Figure 35: mndwi index for April 2007

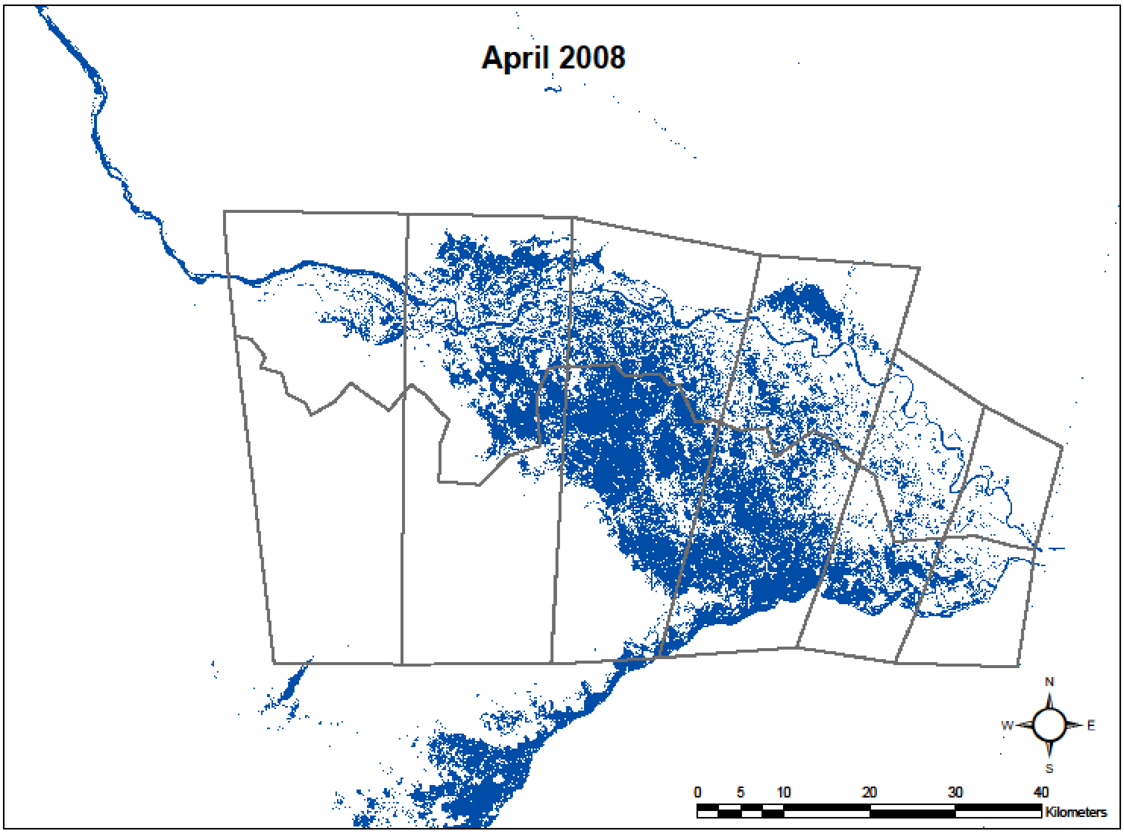

Figure 36: mndwi index for April 2008

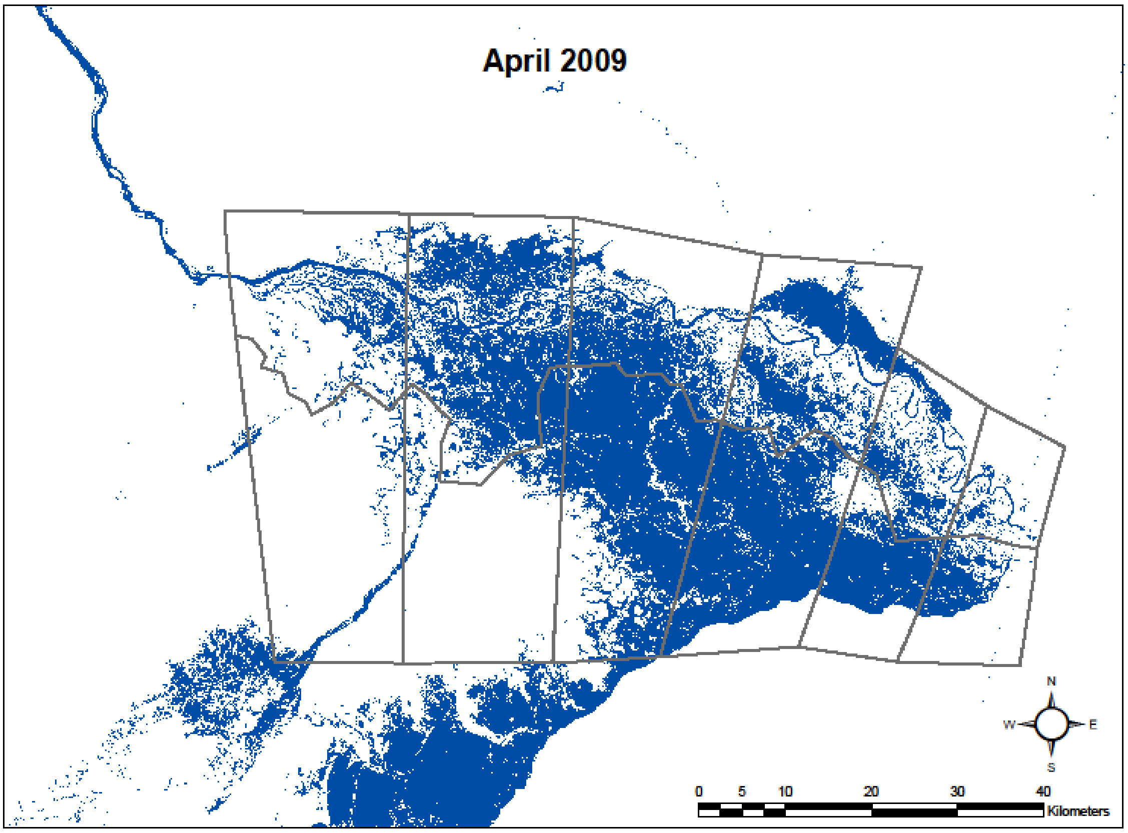

Figure 37: mndwi index for April 2009

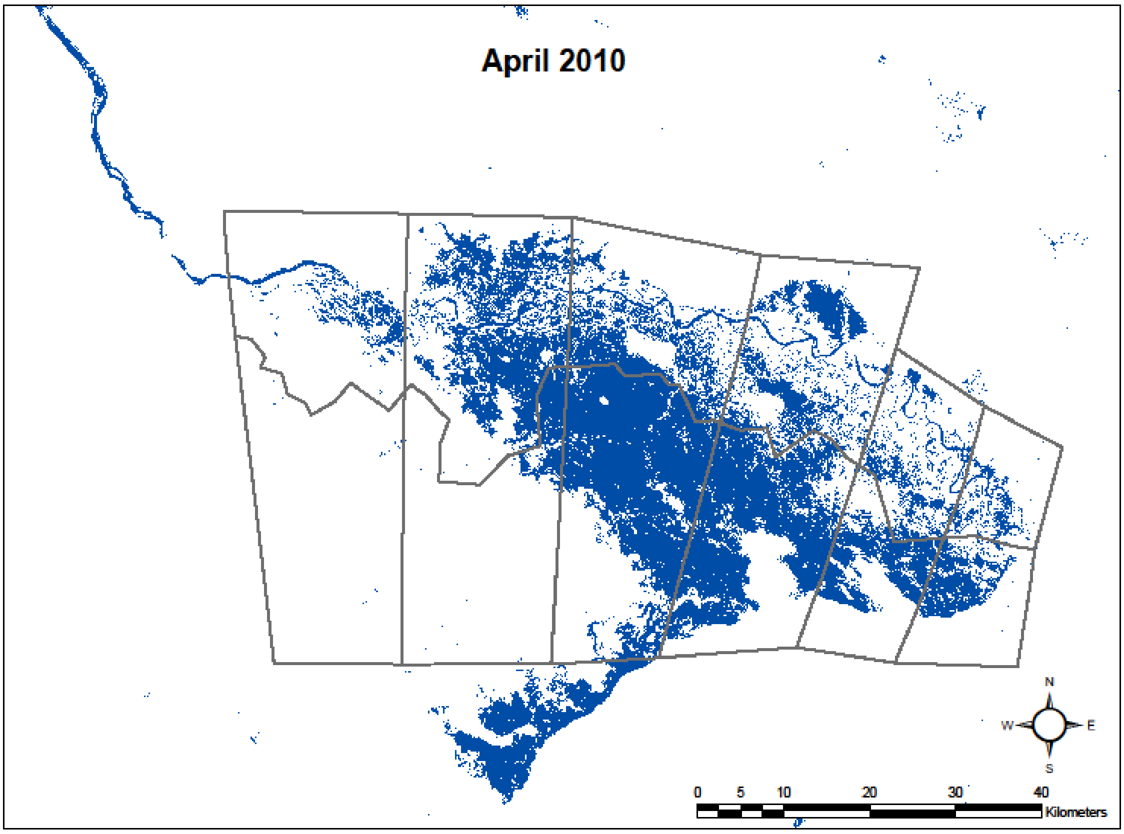

Figure 38: mndwi index for April 2010

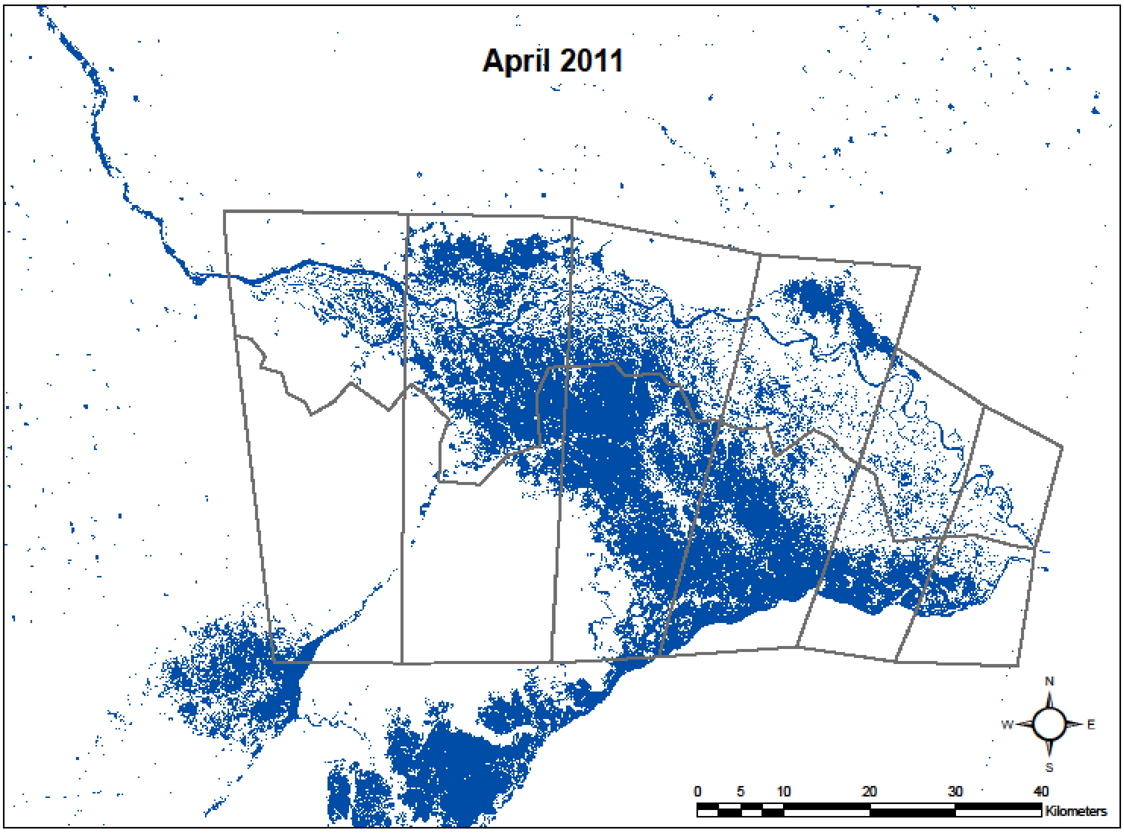

Figure 39: mndwi index for April 2011

As a general conclusion, should be noted that the mulapos are flooded in most of the year studied.

The area which corresponds to the confluence of the Zambezi and the Chobe River is always covered by water. It includes the lowest parts of the floodplain where the mulapos are very close to the main channel making them prone to flooding during the wet season. Further away from the confluence of the two rivers, flooding occurs less often and with less intensity because the area the water has to cover to flood the mulapos is bigger.

The years 2000, 2005 and 2006 are considered to be dry years in terms of runoff and rainfall. The observation of the MNDWI index for these years confirms that; the images show dry or little flooded area at the location of the mulapos.

The volume calculated for the floodplain for these years provide further support for this conclusion: the volume in these years is the lowest. Conversely, the extremely wet years can be observed to register the highest volume in comparison with the others years.

5.3 Assessment of the environmental flow.

5.3.1 Tennant Method

The results for the environmental flow based on the tenant Method are shown in the following lines. Firstly, the yearly mean flow for the whole period was calculated, obtaining as a result 1156 m^3/s.

Tennant Method recommends different base flow in order to obtain flows that correspond with the features described in the next table which values correspond with the following:

Table 13: Recommended base flow regimes in base of the Tennant Method.

Description of flows	Recommended base flow regimes [m^3/s]	
	January-June *	**July-December ***
Flushing or maximum	2312	
Optimum range	693.6 - 1156	
Outstanding	693.6	462.4
Excellent	578	346.8
Good	462.4	231.2
Fair o Degrading	346.8	115.6
Poor or Minimum	115.6	115.6
Severe degradation	115.6-0	115.6-0

In order to specify a monthly environmental flow based on the Tennant Method, the flows which correspond to "Good" (40% for the wet season and 20% for the dry season) and "fair or Degrading" (30% for the wet season and 10% of the dry season) conditions were calculated and the results are shown in the table below.

Table 14: Monthly environmental flow calculated based on Tennant Method for "Good" and "Fair or Degrading" conditions

Year	Monthly Average	Good conditions	Fair or degrading conditions
January	635.10	254.04	190.53
February	1216.46	486.58	364.94
March	2593.00	1037.20	777.90
April	3321.65	1328.66	996.50
May	2490.68	996.27	747.20
June	1320.63	528.25	396.19
July	656.68	131.34	65.67
August	422.33	84.47	42.23
September	323.06	64.61	32.31
October	269.94	53.99	26.99
November	282.49	56.50	28.25
December	379.57	75.91	37.96

These conditions were chosen in order to obtain stream flows that do not damage the ecosystem, but the variability is very low.

Tennant established the maximum condition that corresponds with the maximum flow and this percentage was calculated for the month of April, which corresponds to the maximum stream flow. The results are shown in the following table:

Table 15: Monthly environmental flow based on "Good"condition"from Tennat Method, considering the month of April with the maximum flow

Year	Monthly Average	Good conditions
January	635.10	254.04
February	1216.46	486.58
March	2593.00	1037.20
April	3321.65	3321.65
May	2490.68	996.27
June	1320.63	528.25
July	656.68	131.34
August	422.33	84.47
September	323.06	64.61
October	269.94	53.99
November	282.49	56.50
December	379.57	75.91

5.3.2 Environmental flows with Percentile 90 and 95

The duration curves for each month were made in order to establish a monthly environmental flow with the values that correspond with the 90% and 95%.

The Q95 and Q90 flows are most often used as low flow indices in the government literature and academic sources.
Percentile 90 is widely used for different authors with different reasons; to assess a low flow index (Smakhtin et al.,1995, Smakhtin, 2001), to stablish a minimum flow for aquatic habitat (Yulanti and Burn, 1998), to establish a threshold for warning water managers of critical stream flow levels (Rivera-Ramirez et al. 2002) and to describes limiting stream flow conditions, and is used as a conservative estimator of mean base flow (Wallace and Cox, 2002).

Likewise, Percentile 95 is used as an indicator of extreme low flow conditions (Riggs, 1980, Brilly et al.,1997, Smakhtin,2001, Wallace and Cox .2002, Tharme, 2003), licensing of surface water extractions and effluent discharge limits assessment (Higgs and Petts, 1988, Smakhtin and Toulouse, 1998) and to maintain the natural monthly seasonal variation and to optimize environmental flow rules

The duration curves are shown below:

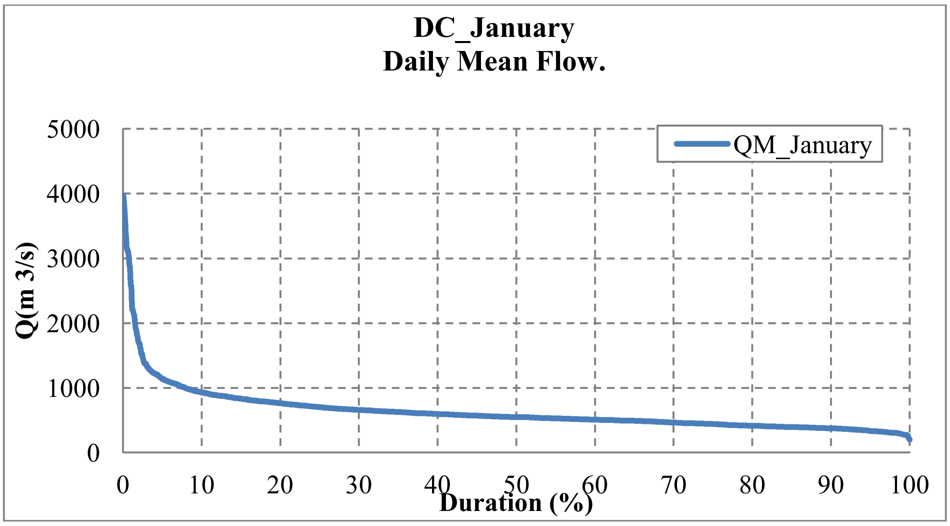

Fig. 40: Duration curve for January

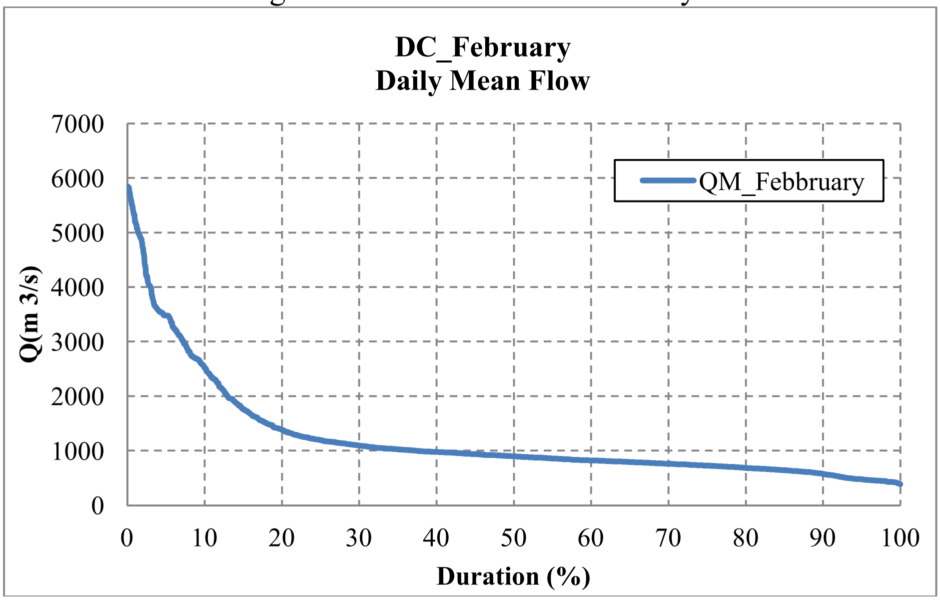

Fig. 41: Duration curve for February

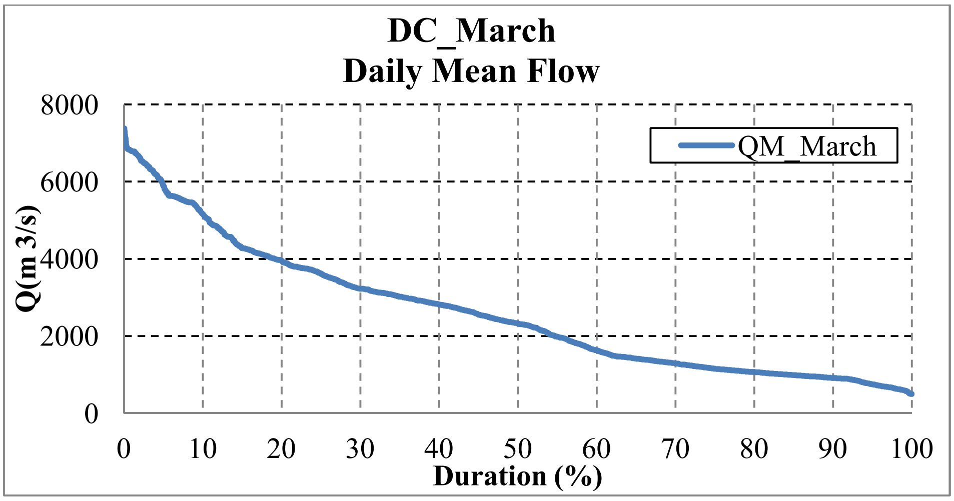

Fig. 42: Duration curve for March

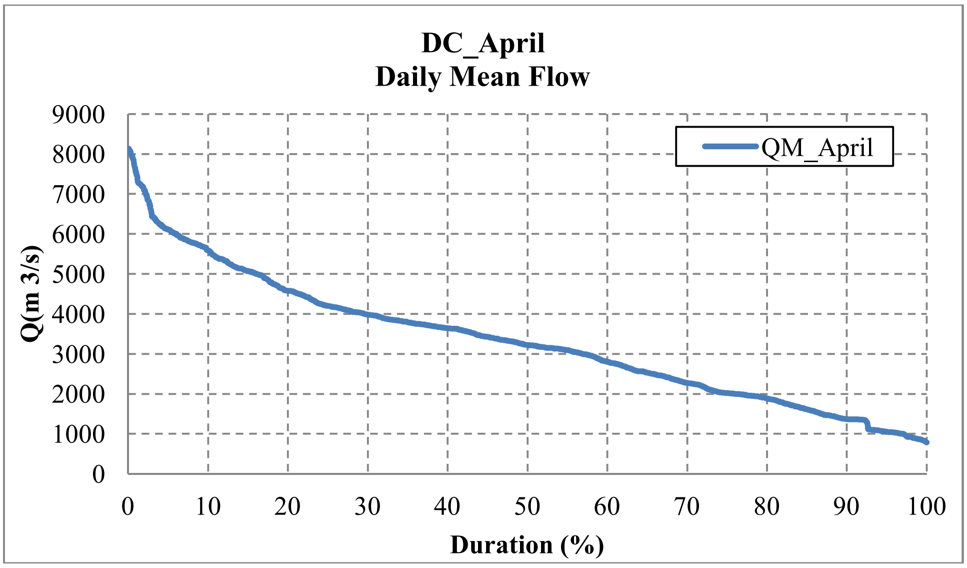

Fig. 43: Duration curve for April

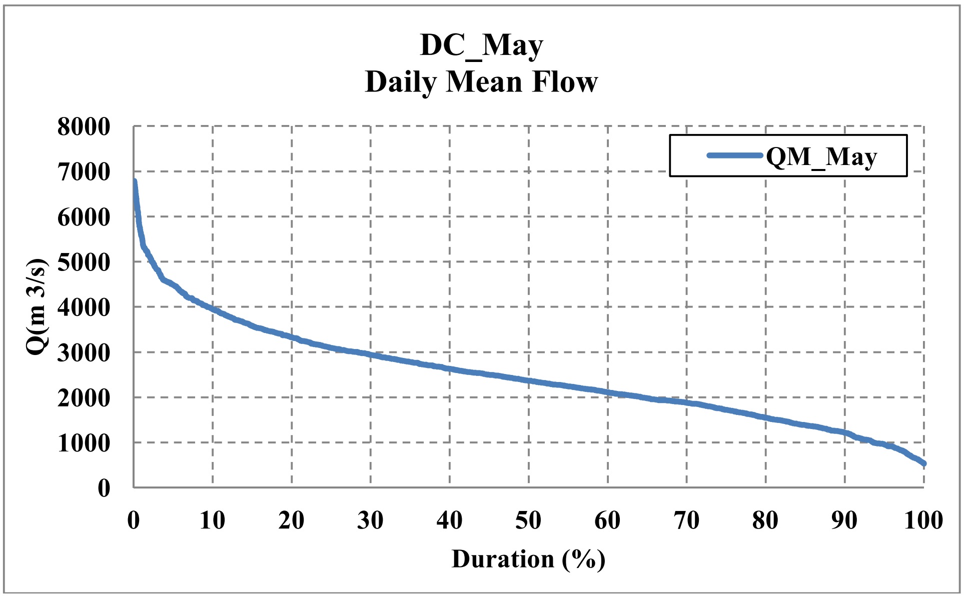

Fig. 44: Duration curve for May

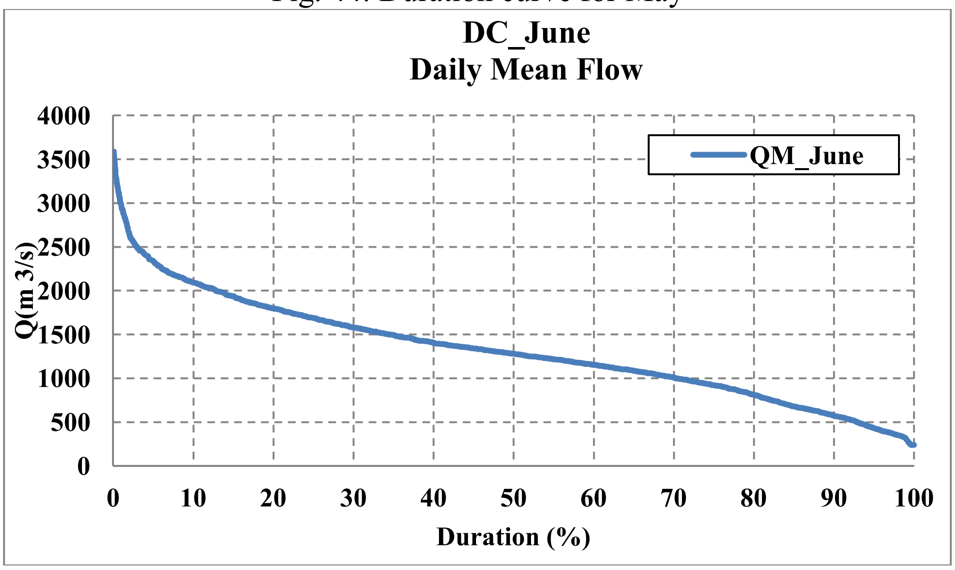

Fig. 45: Duration curve for June

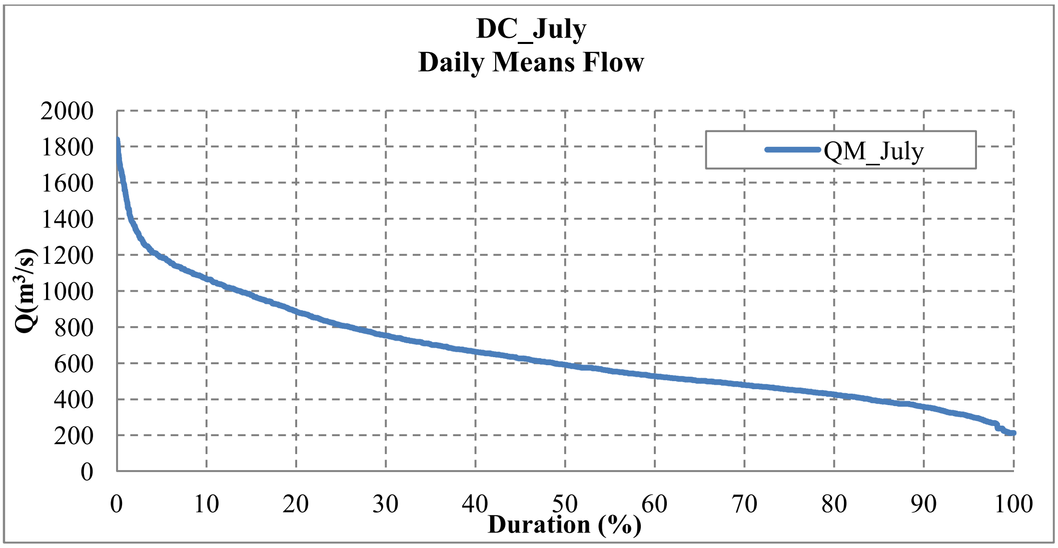

Fig. 46: Duration curve for July

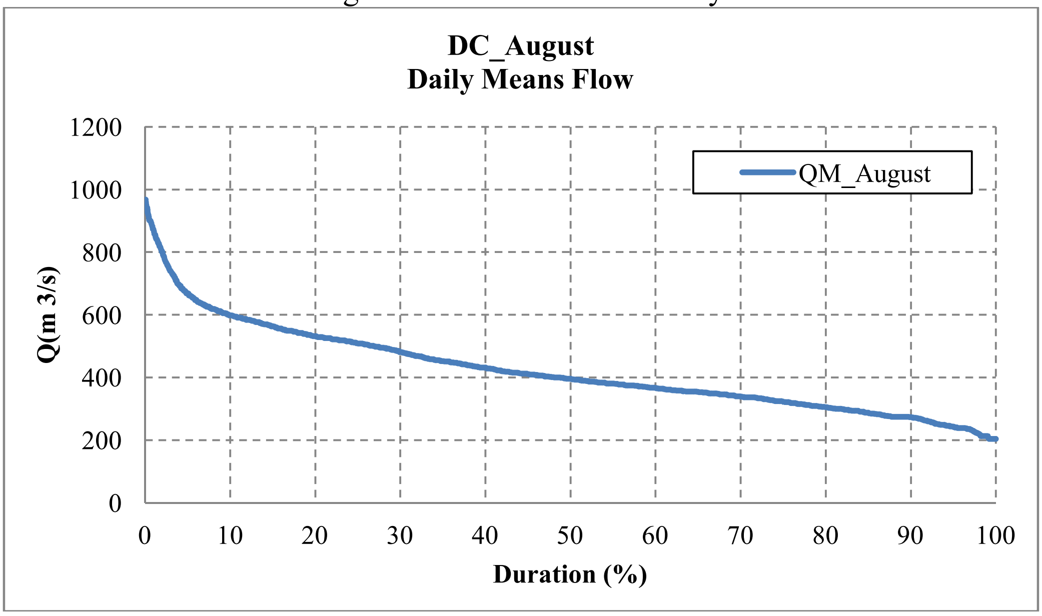

Fig. 47: Duration curve for August

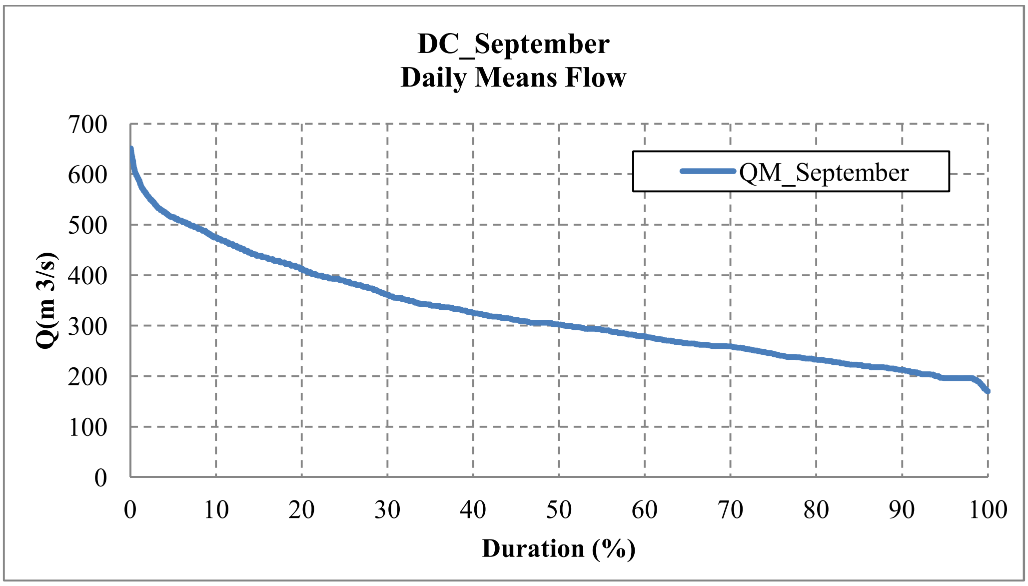

Fig. 48: Duration curve for September

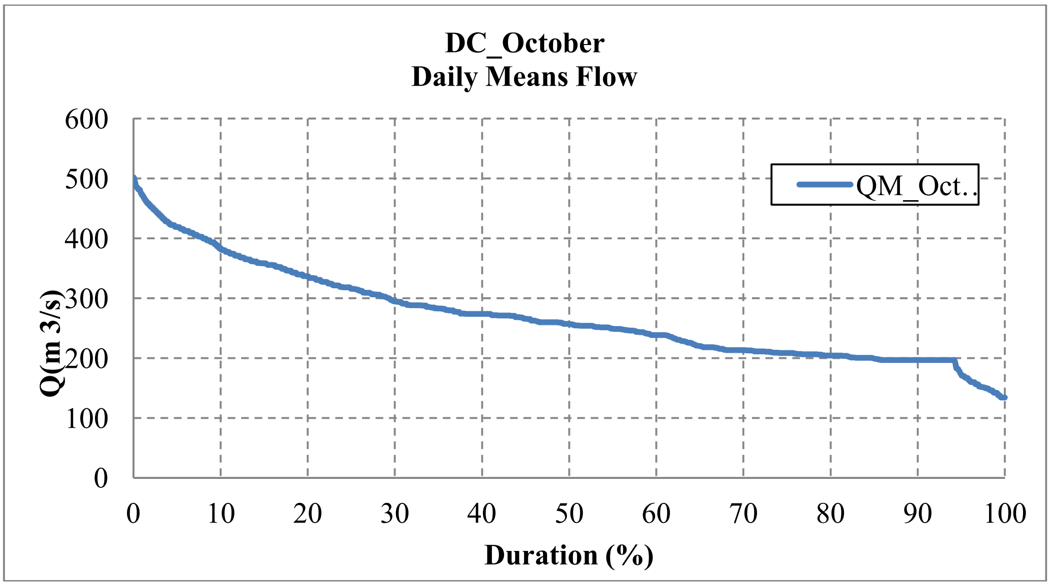

Fig. 49: Duration curve for October

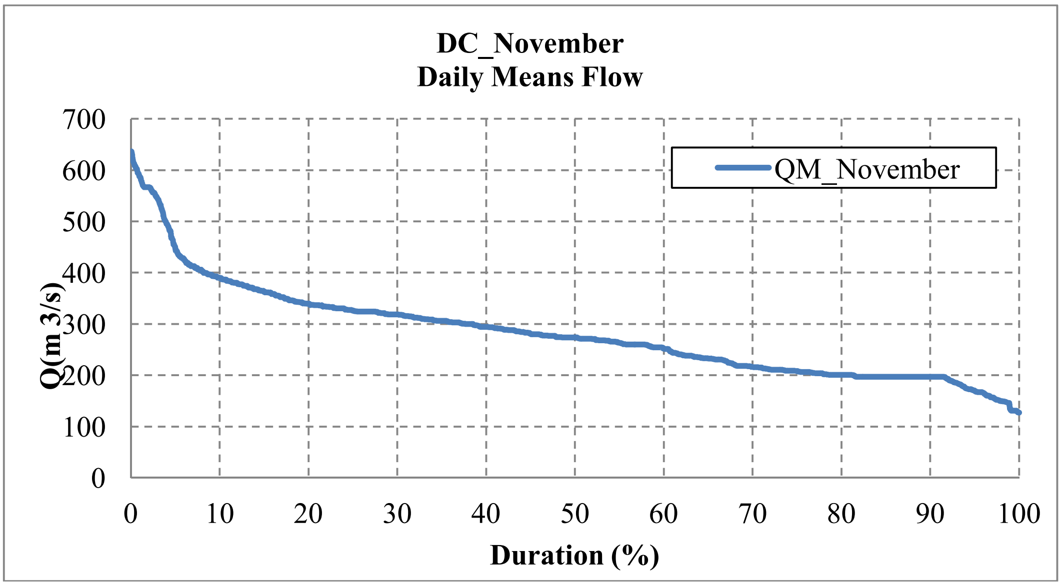

Fig. 50: Duration curve for November

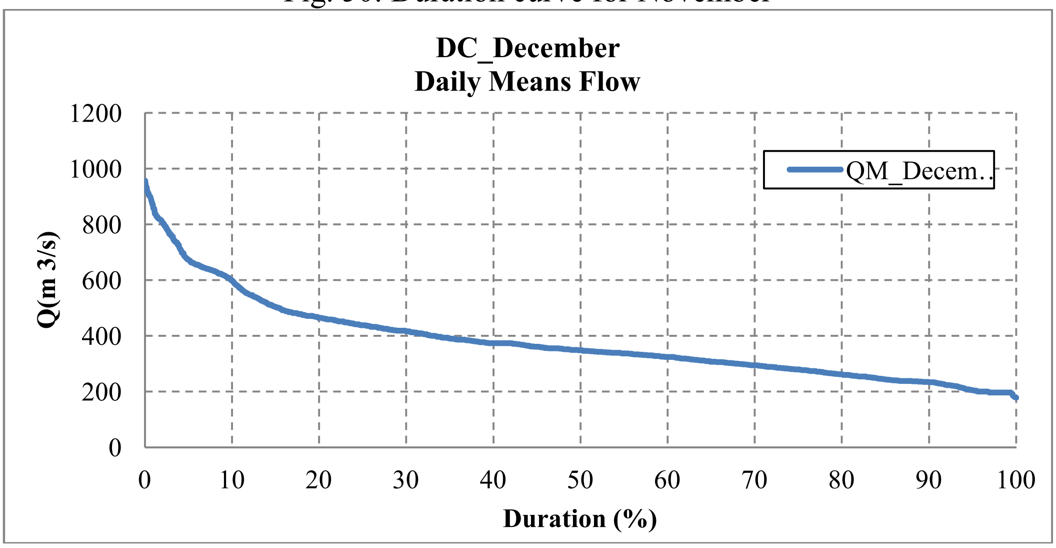

Fig 51: Duration curve for December

The environmental flow calculated in base on the percentile 90 and 95 method, corresponds with the following values:

Table 16: Values of the environmental flow based on the Percentile 90 ad 95 method.

MONTH	P90(m^3/s)	P95(m^3/s)
January	374.94	342.53
February	589.46	472.64
March	942.18	783.08
April	1460.87	1084.08
May	1296.68	991.44
June	585.68	433.45
July	360.69	313.60
August	282.55	255.89
September	228.01	215.06
October	214.63	205.47
November	214.63	201.07
December	248.34	221.59
Average Wet Season	874.97	684.54
Average Dry Season	258.14	235.45

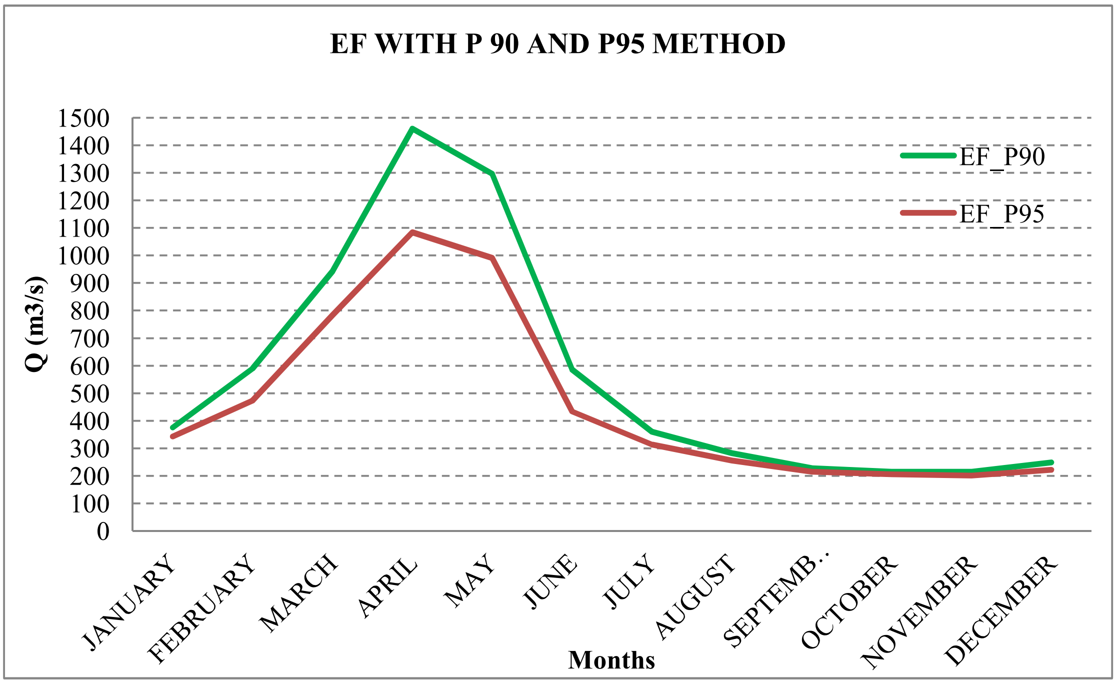

Fig.52: Environmental flow based on the percentile 90 and 95 methods.

5.3.3 Range of Variability Approach and Hydrological Alteration

The Indicators of Hydrologic Alteration were calculated firstly based on the reference condition of the river. There are no assessments available to describe the totally natural condition of the river, but the actual situation is considered as the baseline or natural situation, with no relevant flow regulation. The results for the historical data series from 1965 to 1999 are the following.

Table 17: IHA parameters –only Group 1- for the period from 1965 to 1999.

Period 1965-1999			
Month	Median river flow (m^3/s)	Coefficient of variation	Standar deviation
January	559.6	0.6348	249.5
February	956.5	0.6075	912.5
March	2378	0.9314	1335.5
April	3027	0.5409	1409.0
May	2410	0.5988	973.4
June	1337	0.526	547.5
July	557.1	0.7709	276.9
August	411.5	0.4393	134.7
September	339.6	0.3986	93.4
October	287.3	0.3121	68.7
Noviembre	301.7	0.3066	90.1
Dec-Diciembre	375.8	0.4446	150.6

In the next table, other hydrological indices are shown, regarding the magnitude of river flow in low flow conditions.

Table 18: Parameters of hydrological characterisation for low flows, for the period from 1965 to 1999.

Months	Mean minimum monthly flow (ML) [m^3/s]
January	329.8
February	429
March	656.1
April	986.9
May	981.4
June	384.1
July	292.7
August	251.2
September	214.2
October	187.8
November	178.8
December	224.5

These low flows have a relevant variability, as shown by these indicators:

- Mean Minimum Monthly Flow (m3/s): 426.4
- Standard deviation of the Mean Minimum Monthly Flow (m3/s): 292.1
- Coef. of Variation of the Mean Minimum Monthly Flow (m3/s): 0.7

In the next table, the hydrological indices regarding the high flow conditions are shown.

Table 19: Parameters of hydrological characterisation for high flows, for the period from 1965 to 1999

Months	Mean maximum monthly flow (ML) [m^3/s]
January	1285
February	4814
March	5915
April	6426
May	4936
June	2532
July	1368
August	788
September	565.5
October	443.1
November	564.1
December	805.8

These high flows also present a very high variability, as indicated by these parameters:

- Mean Maximum Monthly Flow (m3/s): 2536.9
- Standard deviation of the Mean Maximum Monthly Flow (m3/s): 2308.7
- Coef. of Variation of the Mean Maximum Monthly Flow (m3/s): 0.9

Following the principles of the RVA method, the parameters shown above were compared with the same values obtained for the future. The results are the following.

Table 20: IHA parameters –only Group 1- for the future scenario (2012-2052)

Period 2012-2052		
Group 1	Median	Coefficient of variation
January	631.4	0.6917
February	1096	1.026
March	1777	0.8242
April	2098	0.6871
May	1532	0.5822
June	828	0.5491
July	448.8	0.4485
August	319	0.3513
September	269.7	0.3237
October	246.4	0.2811
November	284.7	0.2933
December	412.3	0.3297

At this point it is important to remember that the management target in the RVA method is that each parameter could be maintained (under any regulation scenario) within the range of acceptable value (may have both upper and lower bounds, or only a minimum or maximum). And, in the absence of adequate ecological information, is recommended that the ± 1 standard deviation values be the default for setting initial targets. Therefore, this first table contains a very relevant reference for the environmental flows for this river.

In the next table, the hydrological indices regarding the low flow conditions are shown.

Table 21: Parameters of hydrological characterisation for low flows,
for the period from 2012 to 2052.

Months	Mean minimum monthly flow (ML) [m^3/s]
January	392.7
February	456
March	456
April	456
May	456
June	276.5
July	231.2
August	220.4
September	202.5
October	187.5
November	209.1
December	319.8

In the future scenario, the Mean Minimum Monthly Flow is smaller (a 24 % smaller in relation to the actual situation) and the low flows have a smaller variability, in comparison with the actual situation (CV = 0.4), as shown here:

- Mean Minimum Monthly Flow (m3/s): 322.0
- Standard deviation of the Mean Minimum Monthly Flow (m3/s): 113.9
- Coef. of Variation of the Mean Minimum Monthly Flow (m3/s): 0.4

In the next table, the hydrological indices regarding the high flow conditions are shown.

Table 22: Parameters of hydrological characterisation for high flows, for the period from 2012 to 2052.

Months	Mean maximum monthly flow (ML) [m^3/s]
January	2264
February	4341
March	4327
April	4285
May	3035
June	1592
July	820.6
August	590.6
September	485.4
October	714.3
November	714.3
December	714.3

In the future scenario, the Mean Maximum Monthly Flow is smaller (a 21 % smaller) and the variability of high flows is slightly smaller in comparison with the actual situation (CV = 0.9), as shown here:

- Mean Maximum Monthly Flow (m3/s): 1990.3
- Standard deviation of the Mean Maximum Monthly Flow (m3/s): 1597.0
- Coef. of Variation of the Mean Maximum Monthly Flow (m3/s): 0.8

The obtained results for the future scenario show, for the months of December, January and February, stream flow values slightly high that the ones for the natural regime. These months correspond with the end of the dry season and the start of the wet season and it can be due to some reasons. The historical series data used to characterize the natural regime is from the years 1965 to 1999 (34 years) and the one to characterize the runoff in the future is from 2013 to 2051 (38 years) and this difference could affect the results. Another explication could be that the climate change could increase the maximum extreme flows during the wet season from December to May, but due to the human alterations it cannot be noticed during the months of March, April and May.

The expected variation of the stream flow for the future is summarize in the table below.

Table 23: Comparison of the monthly flows between the actual hydrological situation (1965-1999) and the most unfavourable scenario of future hydrological conditions, under river regulation. In the last column is indicated if the future monthly flow fits into the target interval (actual monthly median ± standard deviation).

Month	Median 1965-1999	Median 2012-2052	Difference (actual-future) (m3/s)	Fitting of future flows in reference interval (median ± standard deviation)
January	559.6	631.4	(+)71.8	yes
February	956.5	1096	(+)139.5	yes
March	2378	1777	(-)601	yes
April	3027	2098	(-)929	yes
May	2410	1532	(-)878	yes
June	1337	828	(-)509	yes
July	557.1	448.8	(-)180.3	yes
August	411.5	319	(-)92.5	yes
September	339.6	269.7	(-)69.9	yes
October	287.3	246.4	(-)40.9	yes
November	301.7	284.7	(-)17	yes
December	375.8	412.3	(+)36.5	yes

Considering the data for the wet and the dry season the result is a bit different. The mean stream flow for the wet and dry seasons for the natural regime and future scenario, correspond with the following table:

Table 24: Mean stream flow for the dry and wet season in the natural regime and the future situation

	Natural Regime	future scenario
Mean flow wet season (m^3/s)	1875.69	1306.13
Mean flow dry season (m^3/s)	419.34	327.79

As it is shown in the table, the mean flow for the wet and the dry season would be reduced drastically (more than -10%). The reduced inflow to the catchment affects the flooding and therefore also the water year type of many years.

However, a possible environmental flow for the future scenario could correspond with the following table (based on the data obtained with the IHA software). This situation was made by resting one standard deviation to the median monthly flows, that is, the minimum value in the target interval of the RVA method.

Table 25: Possible environmental flow which was done by resting one standard deviation to the median monthly flows.

Month	Median Monthly Flow	Standar deviation	Environmental Flow
January	559.6	249.5	310.1
February	956.5	912.5	44
March	2378	1335.5	1042.5
April	3027	1409	1618
May	2410	973.4	1436.6
June	1337	547.5	789.5
July	557.1	276.9	280.2
August	411.5	134.7	276.8
September	339.6	93.4	246.2
October	287.3	68.7	218.6
November	301.7	90.1	211.6
December	375.8	150.6	225.2

The obtained environmental flow does not follow a similar pattern than the natural regime. Some of the values are extreme (February, 44m^3/s) and because of that, this method should be used in combination with the others explained before.

In this case, the threshold of 1350 m^3/s is reached during the months of April and May, which means that the floodplain will be flooded during theses months. However, it is necessary to apply the ecological knowledge and to require that the high flows cover the whole floodplain, meaning that 1350 m^3/s must be the minimum flow at least from January to May or June; otherwise the altered flow regime would have bad consequences for the ecosystem and for the socio-economic development of the people living in the region.

5.3.4 Comparative assessment of environmental flow regimes.

The following table summarizes the results of the environmental flow using the Tennant Method, the percentile 90 and 95 and the Range of variability Approach.

Table 26: Monthly environmental flow (m^3/s) obtained by the use of the different methods. Finally, the Range of the minimum-maximum flow obtained in all methods by month is detailed in the last column.

Month	Tennant method		P90 (m3/s)	P95 (m3/s)	RVA (m3/s)
	Good	Fair or degrading			
January	254.04	190.53	374.94	342.53	310.1
February	486.58	364.94	589.46	472.64	44
March	1037.20	777.90	942.18	783.08	1042.5
April	1328.66	996.50	1460.87	1084.08	1618
May	996.27	747.20	1296.68	991.44	1436.6
June	528.25	396.19	585.68	433.45	789.5
July	131.34	65.67	360.69	313.6	280.2
August	84.47	42.23	282.55	255.89	276.8
September	64.61	32.31	228.01	215.06	246.2
October	53.99	26.99	214.63	205.47	218.6
November	56.50	28.25	214.63	201.07	211.6
December	75.91	37.96	248.34	221.59	225.2

These values are considered as an alternative for environmental flows in a future scenario which should be monitored and discussed in a public participation process.

Down here is a plot showing the range of results with the environmental flow methods applied, indicating a river flow variability which is partially related to the median monthly flows in the actual situation.

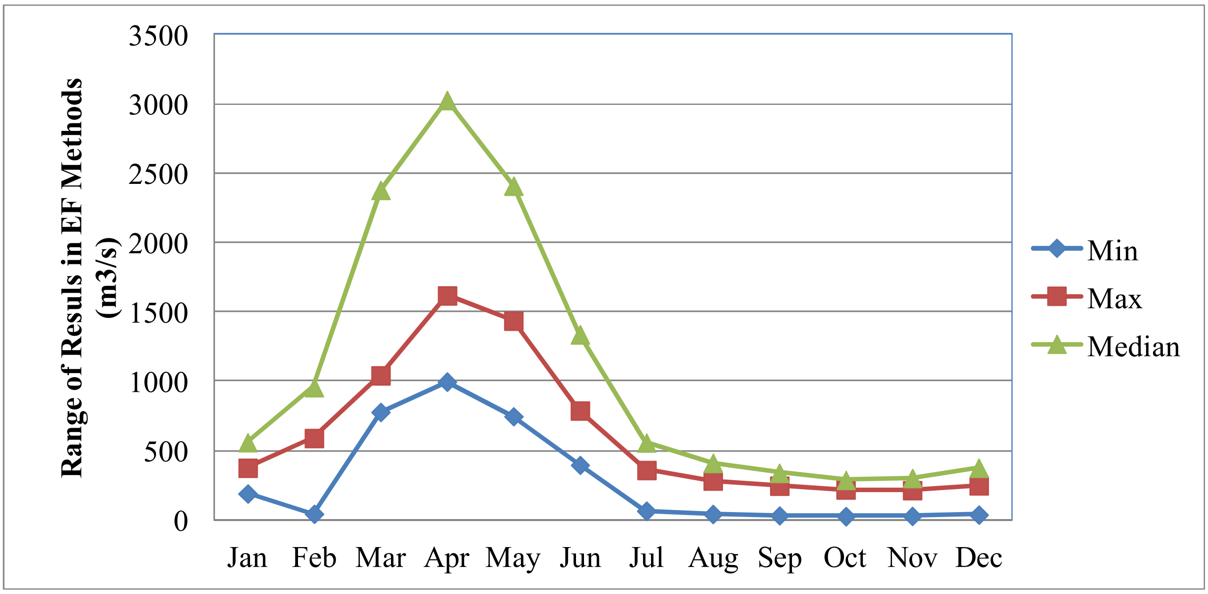

Figure 53: Plot of the range of river flows obtained with the different environmental flow methods (EF) applied in this thesis. By month, the minima (min) and maxima (max) are indicated, and the Medina in the actual situation.

6 Conclusions

The Zambezi River Basin is one of the largest river basins in southern Africa. The Zambezi river is the fourth largest river in Africa after the Congo, Nile and Niger, and is the largest river system in terms of both area and flow volume. The river and associated ecosystems are considered the most important natural ecosystem in southern Africa. The Victoria Falls, one of the Seven Wonders of the World, are found on the Zambezi.

The Zambezi River Basin covers a huge geographical area and there are variations across de whole basin in terms of rainfall, temperature, physical characteristics, land use, economic development and even cultural state of the riparian countries. It is divided into several subbasins and the Easter Caprivi (study area) is defined by the Namibian parts of the Barotse and Cuando/Chobe Basins. It comprises a seasonal floodplain due to its location (in the confluence of two rivers) and its hydrological characteristics which was explained and analyzes before.

Caprivi is more tropical than any other region which surrounds it. It enjoys a higher rainfall, less evaporation and warmer winter than in the rest of Namibia. There are two different seasons: dry and wet season. The rainy season last from January to June; sometimes rains can start in the late November/December peaking from January through April (when about 80% of rain falls). In May rains usually stop and the dry season last from July to December.

The extension of the wetland mostly depends on the amount of water entering the floodplain from upstream, mainly in terms of runoff and rainfall, during the wet season. In the chapter 4, the seasonal distribution of the runoff and rainfall was already demonstrated. Looking at the flow duration curve for Katima Mulilo gauging station (figure 18, chapter 5) it becomes clearer how different wet and dry season are.

During the rainy season, the Zambezi causes massive flooding in the eastern Caprivi and 2/3 of the area can then be covered with water. When the discharge at Katima Mulilo exceeds 1350 m^3/s (World Bank, 2010), flooding begins and the water bodies (mulapos) appear. The flood generally follows a pattern within a yearly cycle. In the Zambezi floodplain there are usually two peaks. The first one, appear in the early season (February or March), when the “bankfull” stage is reached, the river breaks its banks and the water spreads out across the floodplain. Then, the water level in the channel appears to drop but begins to rise again when the water in the lowest areas can no longer be accommodated. It is estimated that the water remains at its highest level for only about two weeks, and in May it starts to withdrawn. Within this Master Thesis, the determination of the mulapos was done using the month of May for 2008 (a very wet year). Looking at the picture which shows the mndwi index (figure 24, chapter 5), the mulapos are colored in blue and correspond with the lowest areas that still remain flooded. Once the mulapos have been determined, a comparative assessment of the different flooding during the years 2000-2011 were performed. As a general conclusion, should be noted that the mulapos are flooded in most of the year studied, as it was explained before. The area which corresponds to the confluence of the Zambezi and the Chobe River is always covered by water; further away from this confluence, flooding occurs less often and with less intensity.

River-floodplain system provide important habitat for biota and are integrated into a single dynamic system. The rivers themselves have a relatively low primary productivity, but it is the annual inundation of the adjacent grasslands which makes the floodplain such a rich environment.

In the chapter 3 the biodiversity in the floodplain was discussed, highlighting the importance of the wide variety of fish due to their ecological and social value. The annual flooding can generate and sustain large fish populations as a result of the extensive opportunities for feeding and growth. During this period, biomass increases substantially and the main feeding season occurs. Similarly, fish tend to spawn so that the juveniles can be on the floodplain during the flood season and have access to plentiful food supplies. The availability of food during the wet season ensures fishing is possible in the main channel during the dry season, when the water and fish move back to the main channel because they will have grown sufficiently large.

The vegetation in the floodplain consists mainly of floodplain types, with flood grassland and swamp vegetation. It is formed by reeds and sedges which vary in size. This vegetation provides the habitat for the fauna species that live in the floodplain and are used by fishes to spawn. The annual water movement from the river to the floodplain ensures seeds dispersal, guaranteeing its renewal and the persistence of the natural habitat.

The sediments brought down by the floods determine the formation of special elements such as sandbanks or small islands which will help to maintain the vegetation existent and to develop new ones, building habitats for the fauna species.

The floodplain is also of great importance for birds, providing them food and shelter.

The annual flooding facilitates agricultural practices during the dry season. By June, the water begins to subside and the aquatic environment becomes progressively drier, transforming most of the area in an agricultural zone. The remaining soil moisture is then utilized by farmers for their crops, reducing the amount of water needed.

As is demonstrated by the conclusions above, floods play an important role both during the wet season, and the subsequent dry season. Therefore it is important to ensure a minimum environmental flow to preserve the dynamics of the river-floodplain system.

As it was mentioned before, flooding in the Eastern Caprivi occur when the discharge at Katima Mulilo gauging station exceeds 1350 m^3/s. This data is very important and should be reached every year during the wet season as the biodiversity in the floodplain depends mainly on it. The mulapos should also be flooded once per year. To design an environmental flow at the Katima Mulilo gauging station, this consideration should be taking into account. To preserve biodiversity in the floodplain, it should be flooded every wet season and, to accomplish that, runoff should be higher than 1350 m^3/s. Likewise and considering the results of the methods studied for the environmental flow, the percentile 90 method shows the most convenient river flow to preserve the natural conditions of the Zambezi River.

Furthermore, socio-economic aspects should be considered. The floods are essential for the main economic activities, thus providing livelihood for the population on the floodplain during the wet and dry season.

7 Further research

In the introduction of this Master Thesis, several research objectives had been exposed. During its performance, several research lines were set up, which are explained below.

- To improve the techniques to determine water bodies in floodplains. Mulapos are defined as important features which should be considered to ensure the ecological diversity of the floodplain, but there is little information about them. The MNDWI index is used to define water bodies but this technique could have greater efficiency and precision in combination with other techniques with a higher resolution (using others satellites images combined with field work results).
- To develop a more detailed comparative assessment of the water volume in the mulapos during a longer time period. For that, more satellite images are required, to obtain a more accurate result. The volume variations in the floodplain could be used for the study of the climate change, its implications and consequences.
- Another interesting research topic for the future could be to estimate the carbon storage of the wetlands in the study area. Carbon storage probably compromises the most studied Ecosystem Service, and its quantification in wetlands and floodplains remains difficult, and it is a great challenge nowadays in these large ecosystems.
- To study the environmental flow in the Zambezi River using other methodologies, like the Building Block Method (for example). A research about the development of a new methodology for e-flows in rivers with big wetlands could be very useful, due to the little literature about this topic.
- To improve the analyses of inundation and floodplain habitats with new methods recently proposed , such as the Area-Duration-Frequency (ADF) curves and the values of expected annual habitat (EAH) analogous to expected annual damages (EAD) used in flood risk. These methods have been recently applied in the Lower San Joaquin River in California, and a scientific article has been accepted in August 15th, 2013, in the Journal of Water Resources Planning and Management (An Integrative Method for Quantifying Floodplain Habitat. M.K. Matella and K.J. PE).

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9 Annex 1. Tables

Table 1. Yearly runoff data from 1943-2010 (excluding the years from 1955-1964)

Year	Mean Flow (m3/s)
1943	718.329
1944	997.060
1945	1090.243
1946	713.495
1947	1320.595
1948	1694.529
1949	403.266
1950	1389.766
1951	1291.385
1952	1444.616
1953	1444.724
1954	1423.056
1965	1079.370
1966	1276.479
1967	1111.578
1968	1920.837
1969	2075.541
1970	1675.202
1971	1274.101
1972	965.293
1973	707.928
1974	1241.818
1975	1708.614
1976	1751.798
1977	1317.066
1978	1971.137
1979	1706.830
1980	1560.393
1981	1302.907
1982	770.797
1983	724.118
1984	818.407
1985	906.820
1986	965.502
1987	981.666
1988	926.720
1989	1557.184
1990	631.447
1991	977.384
1992	550.010
1993	1109.135
1994	756.961
1995	522.549
1996	432.875
1997	717.784
1998	1264.673
1999	1212.149
2000	917.142
2001	1377.610
2002	857.358
2003	1220.023
2004	1456.751
2005	680.430
2006	1020.389
2007	1641.437
2008	1407.862
2010	1859.509

Source: GRDC

Table 2. Precipitation data for the Caprivi Region

Year	**P total(mm)**	**Average (mm)**	**P wet season (mm)**	**P dry season (mm)**
1943	572.50	47.71	346.30	226.20
1944	895.40	74.62	674.97	220.43
1945	399.97	33.33	294.80	105.17
1946	828.53	69.04	586.77	241.77
1947	391.93	32.66	294.40	97.53
1948	883.60	73.63	592.10	291.50
1949	561.40	46.78	417.60	143.80
1950	587.93	48.99	311.13	276.80
1951	634.37	52.86	333.90	300.47
1952	980.77	81.73	620.47	360.30
1953	807.43	67.29	560.17	247.27
1954	848.60	70.72	564.97	283.63
1955	1011.03	84.25	644.53	366.50
1956	645.50	53.79	421.13	224.37
1957	554.43	46.20	377.10	177.33
1958	1290.60	107.55	877.47	413.13
1959	672.23	56.02	367.67	304.57
1960	548.90	45.74	349.50	199.40
1961	746.50	62.21	556.10	190.40
1962	495.20	41.27	350.80	144.40
1963	668.67	55.72	357.73	310.93
1964	504.33	42.03	192.53	311.80
1965	510.23	42.52	248.67	261.57
1966	719.90	59.99	556.07	163.83
1967	614.67	51.22	434.43	180.23
1968	635.67	52.97	380.90	254.77
1969	663.57	55.30	425.73	237.83
1970	514.77	42.90	150.07	364.70

1971	663.13	55.26	378.03	285.10
1972	860.03	71.67	666.50	193.53
1973	524.40	43.70	370.93	153.47
1974	1017.77	84.81	662.03	355.73
1975	773.90	64.49	437.27	336.63
1976	612.47	51.04	449.13	163.33
1977	903.83	75.32	678.80	225.03
1978	902.03	75.17	550.67	351.37
1979	458.10	38.18	249.23	208.87
1980	571.47	47.62	303.17	268.30
1981	675.73	56.31	521.37	154.37
1982	393.27	32.77	216.77	176.50
1983	459.33	38.28	291.10	168.23
1984	528.20	44.02	259.23	268.97
1985	592.80	49.40	408.40	184.40
1986	606.17	50.51	334.80	271.37
1987	502.90	41.91	272.80	230.10
1988	765.43	63.79	533.13	232.30
1989	629.17	52.43	426.60	202.57
1990	544.50	45.38	428.67	115.83
1991	516.57	43.05	390.93	125.63
1992	578.83	48.24	250.43	328.40
1993	573.07	47.76	395.57	177.50
1994	480.43	40.04	313.17	167.27
1995	403.20	33.60	257.03	146.17
1996	487.83	40.65	317.90	169.93
1997	590.27	49.19	420.67	169.60
1998	694.30	57.86	554.50	139.80
1999	596.63	49.72	310.67	285.97
2000	675.87	56.32	526.27	149.60
2001	682.33	56.86	447.27	235.07
2002	573.67	47.81	355.27	218.40

2003	496.70	41.39	276.63	220.07
2004	742.93	61.91	582.80	160.13
2005	544.77	45.40	332.07	212.70
2006	751.60	62.63	409.67	341.93
2007	648.00	54.00	409.67	238.33
2008	648.00	54.00	409.67	238.33
2009	614.33	51.19	376.00	238.33
Mean [mm]	646.46	53.87	418.59	227.87

Source: University of East Anglia Climatic Research Unit (CRU). [Phil Jones, Ian Harris]. CRU Times Series (TS) high resolution gridded datasets, [Internet]. NCAS British Atmospheric Data Centre, 2008, Date of citation. Available from htpp://badc.nerc.ac.uk/view/badc.nerc.ac.uk_ATOM_dataent_1256223773328276

Table 3. Average temperature for the Caprivi Region

Year	**Mean (ºC)**
1943	22.98
1944	22.79
1945	22.79
1946	22.81
1947	23.20
1948	22.67
1949	23.07
1950	23.04
1951	22.71
1952	22.68
1953	22.27
1954	22.16
1955	22.44
1956	22.54
1957	22.80
1958	22.91
1959	23.14
1960	22.87
1961	22.61
1962	22.49
1963	21.94
1964	22.42
1965	22.32
1966	22.48
1967	22.79
1968	22.75
1969	22.97
1970	22.96
1971	23.00
1972	22.27
1973	23.28
1974	22.02
1975	21.96
1976	21.82
1977	22.59
1978	22.54
1979	22.54
1980	22.54
1981	22.30
1982	23.33
1983	23.21
1984	23.26
1985	23.06
1986	22.93
1987	23.62
1988	23.50
1989	22.75
1990	23.39
1991	23.37
1992	23.48
1993	23.23
1994	23.24
1995	24.05
1996	24.11
1997	24.10
1998	24.96
1999	24.24
2000	23.94
2001	23.99
2002	24.03
2003	24.74
2004	23.80
2005	24.90
2006	23.43
2007	23.11
2008	23.16
2009	24.02
Mean [mm]	22.93

Source: CRU

Table 4. Potencial evapotranspiration for Caprivi Region

Years	PET(mm/year)
1901	1434.47
1902	1435.27
1903	1435.37
1904	1415.03
1905	1427.33
1906	1409.03
1907	1395.67
1908	1427.37
1909	1409.33
1910	1406
1911	1405.03
1912	1424.97
1913	1432.33
1914	1428.17
1915	1404.13
1916	1421.97
1917	1416.07
1918	1367.33
1919	1381.43
1920	1402.9
1921	1411.77
1922	1436.37
1923	1428.4
1924	1401.43
1925	1385.97
1926	1395.27
1927	1402.57
1928	1432
1929	1420.43
1930	1411.03
1931	1450.2
1932	1424.5
1933	1408.73
1934	1402.03
1935	1417.03
1936	1385.43
1937	1365.2
1938	1406.87

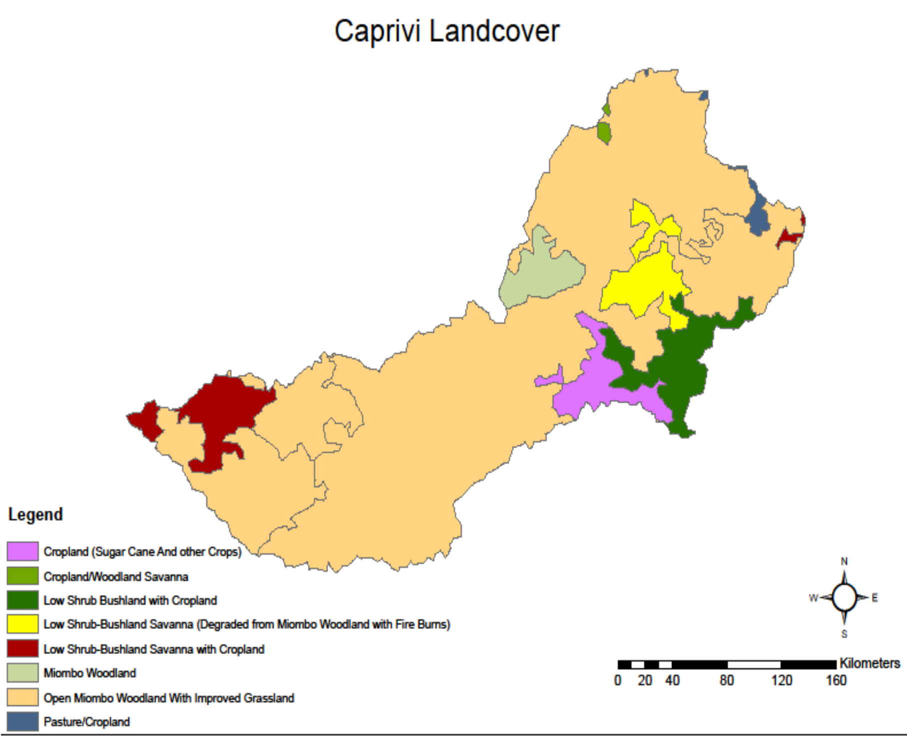
1939	1342.03
1940	1404.03
1941	1414.63
1942	1430.33
1943	1408.1
1944	1416.9
1945	1414.1
1946	1433.43
1947	1437.67
1948	1391.27
1949	1451
1950	1410.2
1951	1387.63
1952	1395.33
1953	1314.1
1954	1384.6
1955	1372.87
1956	1369.57
1957	1438.3
1958	1350.4
1959	1460.9
1960	1438.8
1961	1381.27
1962	1394.7
1963	1375.47
1964	1457.73
1965	1459.2
1966	1407.2
1967	1371
1968	1448.67
1969	1316.1
1970	1480.73
1971	1438.83
1972	1417.57
1973	1423.7
1974	1306.8
1975	1385.27
1976	1311.23
1977	1405.43

1978	1315.63
1979	1397.63
1980	1425.4
1981	1415.2
1982	1452.43
1983	1467.2
1984	1460.43
1985	1428.87
1986	1385.23
1987	1529.2
1988	1436.5
1989	1434.33
1990	1473.17
1991	1425.5
1992	1508.07
1993	1413.53
1994	1474.6
1995	1478.67
1996	1466.83
1997	1458.6
1998	1474.77
1999	1487.07
2000	1434.2
2001	1438.13
2002	1494.9
2003	1517.83
2004	1446.73
2005	1517.17
2006	1419.2
2007	1430.17
2008	1438.3
2009	1495.1

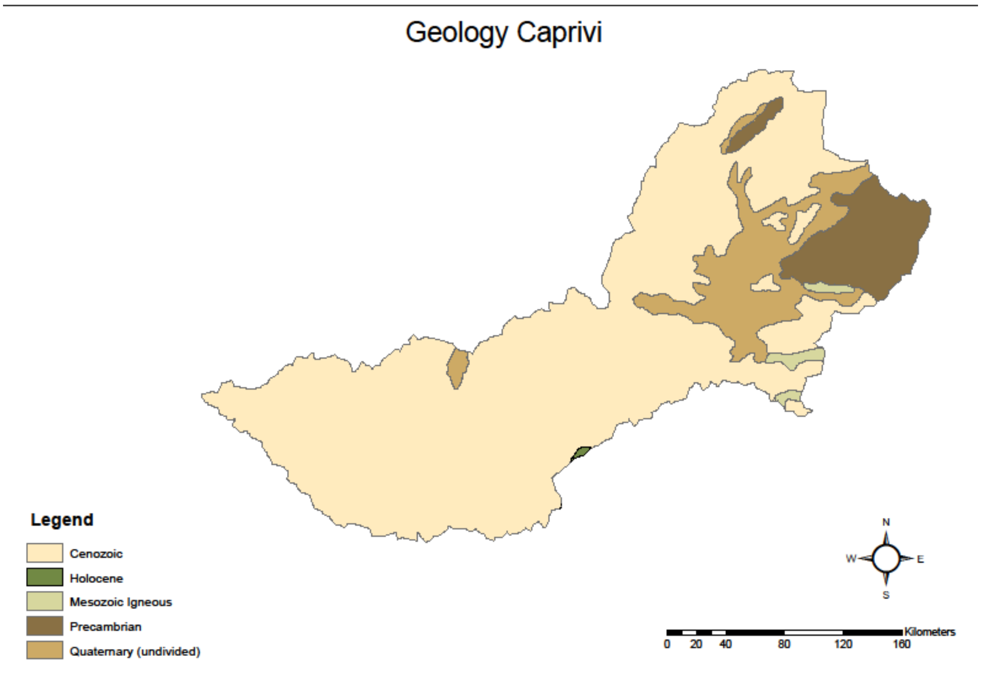
.
Source:CRU

10 Annex 2. Maps.

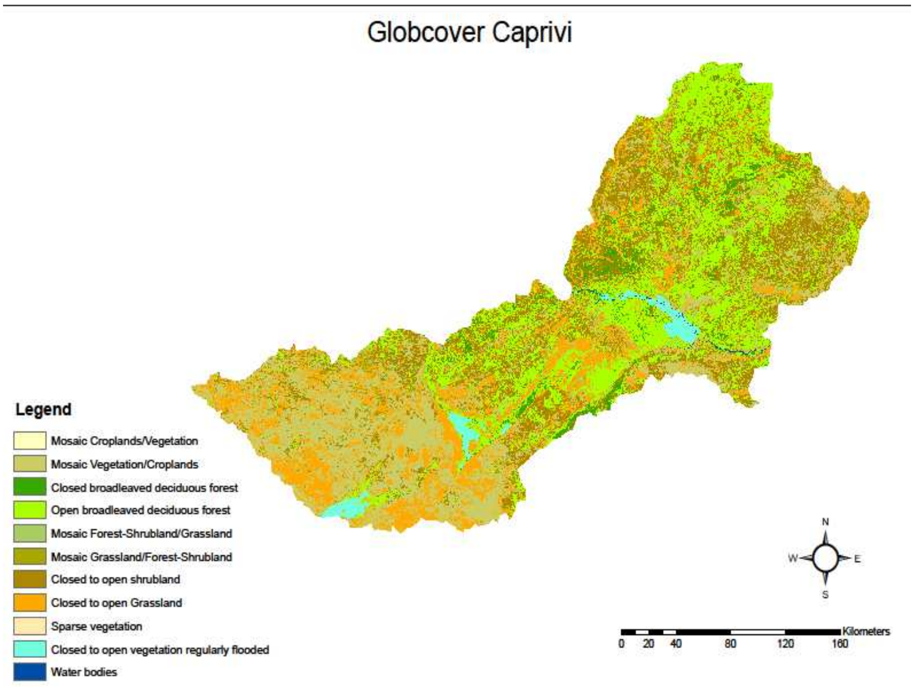
Map 1. Caprivi Landcover



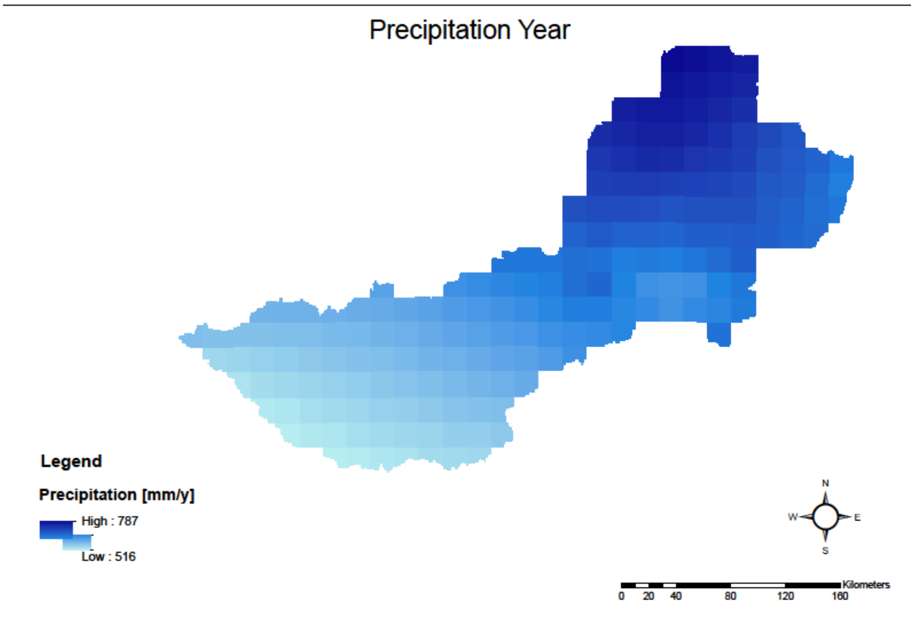
Map 2. Caprivi Geology



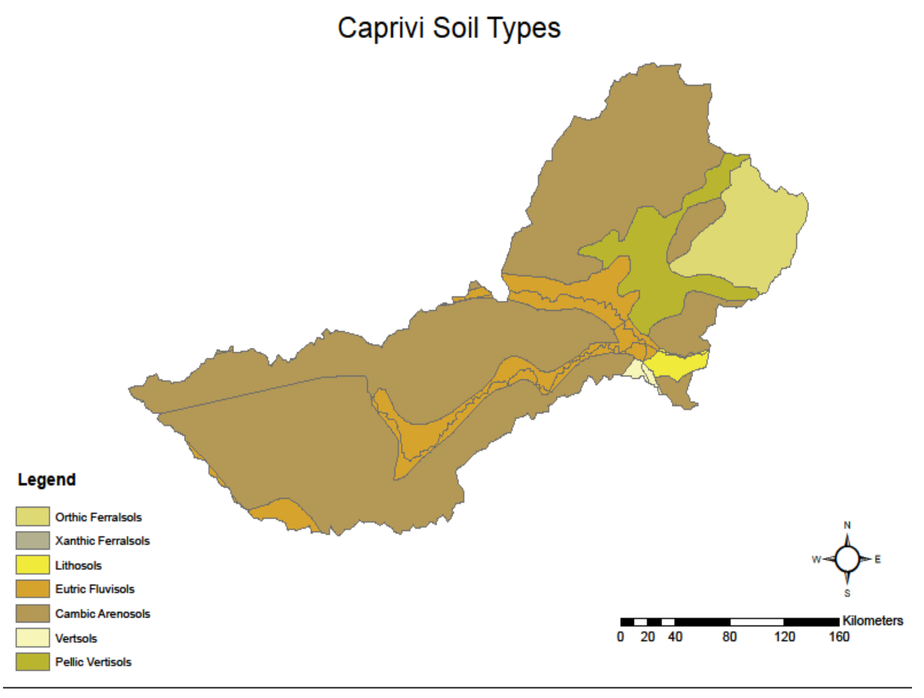
Map 3. Caprivi Globcover



Map 4. Caprivi Precipitation Year



Map 5. Caprivi soil types



Map 6. Caprivi DEM