KEY ECOSYSTEMS AND ECOSYSTEM SERVICES IN THE OMO-TURKANA AND ZAMBEZI RIVER BASINS

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Abbreviations

DAF	Decision Analytic Framework
DoA	Description of Actions
ES	Ecosystem Service
IHA	Index of Hydrologic Alteration
IUCN	International Union for the Conservation of Nature
KBA	Key Biodiversity Area
OTB:	Omo-Turkana Basin
WEF	Water Energy Food nexus
WLRC	Water and Land Resource Centre at Addis Ababa University
ZRB:	Zambezi River Basin

EXECUTIVE SUMMARY

Ecosystems provide important values to human health and wellbeing. The concept of ecosystem services highlights these values in order for them to be included in overall land and water related decision-making. Global changes in climate, land use and river modifications have far-reaching consequences for the availability of ecosystem services. For the OTB and the ZRB we present a comprehensive overview of dominant ecosystems and the services they deliver. We further analyse how the demand for ecosystem services by human populations is distributed spatially and has changed over time. We outline changes in ecosystem service availability due to anthropogenic modifications in river systems and develop pathways for ecosystem management.

The most important ecosystems in both basins are rivers, lakes, riparian wetlands, grass- and shrublands as well as tropical dry to humid forests. These ecosystems provide water but also food from fisheries, flood recession agriculture, livestock grazing, hunting and gathering activities. Wooded ecosystems also provide energy through firewood and charcoal. With the help of technical modifications such as dams and diversions, rivers also provide electricity and irrigation, but such services are covered in other deliverables. Ecosystems furthermore have important regulating functions, for example through flow and flood regulation of rivers and carbon storage with importance for the global climate. Ecosystems provide cultural services by giving a sense of place and identification to inhabitants as well as touristic potential to visitors. Finally, supporting services are for example soil formation and sediment retention. This is particularly important for agricultural areas in floodplains and dams affected by siltation.

With ongoing urbanization and electrification, the overall demand for ecosystem services in both basins has shifted from rural to urban areas. Urban populations use all kind of commodities, such as food products and charcoal and need sufficient amounts of clean water for drinking and domestic supply. All these products would not be available without the functioning of the ecosystems described in this deliverable. Yet, we emphasize that access to infrastructure in more urbanized regions allows people to satisfy their basic needs from more remote sources, while rural populations depend more immediately on the ecosystems in their direct vicinity. Especially in the larger urban areas of the ZRB, with the size of urban areas, the demand for other types of ecosystem services increases. This includes for example the regulation of urban heat island effects through “green infrastructure” and the filtering of polluted surface waters through floating vegetation.

Changes in ecosystem service availability is considerably different between the two river basins. Some of the dams in the Zambezi basin have been in operation for more than 50 years. Modifications of upstream and downstream ecosystems, associated with changed flow dynamics and impoundments are somewhat established and people have learned to live with them. However, the Zambezi delta in Mozambique and wetlands such as the Kafue flats are still experiencing the long-term effects of hydrological changes and related loss of habitat and biodiversity. In contrast, men-made reservoirs have also provided new sources for fisheries, especially through the introduced kapenta fishes in Lake Kariba, Itezhi-Tezhi and Cahora Bassa reservoirs. Further changes are deforestation, water pollution and associated floating plant invasions. The OTB was until recently characterized by free-flowing rivers. New dam construction and diversions for irrigation, most notably Gibe 3 dam and the Kuraz sugar project are likely to change flow dynamics in a way that affects both flood recession agriculture and grazing grounds in riparian areas and the Omo delta. Fish stocks in Lake Turkana depend on variations between high and low inflows from the river and might decrease with overall reducing lake levels. In contrast - land cover in the OTB is on a positive trajectory. Forest cover shows an increasing trend, potentially associated with improved access to electricity that leads to a decreasing demand for fuelwood in urban areas, especially from charcoal.

For each basin, we discuss potential ecosystem management pathways. For example in the ZRB, reservoir release strategies for environmental flows have been part of the design of Itezhi-Thezi

dam. However, we show that years with releases have been sporadic and the only regular sequence could be observed between 2007 and 2011. We show that whenever they happened, releases were successful in restoring surface water extents and have potentially helped controlling invasive floating weeds. In the OTB, reservoir release strategies are part of the environmental impact assessment, however, the suggested measures seem incomplete and it is unclear, how far they have already been implemented. As additional measures we explore the possibility to create artificial breaches in the levees of the Omo river in the delta area, in order to restore flooded areas for recession agriculture and grazing. We suggest forest and land cover management, in order to further increase forest cover.

We conclude that while increasing urbanisation is helping to reduce overall pressure on forest and land, the competition for water-related services from free flowing versus modified rivers is rising. Both basins require active monitoring and adaptive management to take into account the demands of their most vulnerable rural populations.

1. INTRODUCTION

1.1 RATIONALE

The concept of the Water-Energy-Food nexus is relatively defined for the Energy and Food parts, as they deal with the economically quantifiable business sectors of hydropower production and agriculture. At the same time, it remains ambiguous, what the Water in the WEF-nexus stands for. One could think it mainly addresses water for drinking and industrial uses. Yet, in the case of the DAFNE project, we extend this definition by far, in that we include all ecosystem services depending on and influencing water availability. The ecosystem services concept is now widely accepted as a concept to give value to the life-supporting functions of ecosystems [Costanza et al., 1997]. In the face of climate change, global population growth and massive loss of biodiversity it is important to realize that there are planetary boundaries that are not taken into account in current economic systems [Rockström et al., 2009]. An integrated model intending to cover the full width of water needs and availabilities can therefore not ignore the value of ecosystems, even if they are beyond the possibilities of monetary quantification. Deliverable 3.4 addresses key ecosystems and ecosystem services in the Zambezi (ZRB) and Omo-Turkana basins (OTB) other than hydropower production and irrigation agriculture (these are addressed in other deliverables).

The description of the deliverable in the DoA reads “Characterisation of the response (criteria and indicators) of key selected terrestrial and aquatic ecosystems to climate and water availability forcing and model-based quantification of ecosystem services”. Limited data availability made it difficult to fully achieve this goal for the entirety of the two basins. Yet, in this document we provide a substantial analysis of what ecosystems there are, what services they provide and we quantify in a spatially explicit way what changes have occurred in the past that can be related to climatic conditions and overall water availability. We used this information to provide pathways for future ecosystem management that will feed into the overall WEF and DAF models of the DAFNE project. The various spatial analyses that we present in the form of maps will provide inputs for further analyses in the DAFNE project and can already be used for spatially explicit decision-making.

1.2 APPROACH

The first two sections in the chapters of each basin are based on a review of available literature to outline the most important ecosystems and provide an overview of ecosystem services. The other chapters are mostly driven by spatial data from remote sensing and publicly available datasets. We present a framework based on various spatial analyses, to determine where ecosystem services are most needed, but also where they are most threatened through human activities, including the construction of hydropower dams, expansion of irrigation agriculture and climate change. Given the size of the areas and the limited data availability, it is not possible to use a consistent methodology that consistently covers all ecosystem services in a similar way. Wherever possible, we define indicators, mostly based on remote sensing data, to locate and quantify certain ecosystem services in relation to water availability. Due to the diversity in approaches, we describe methods for this within each section. Finally, we present suggestions, how ecosystem management can maintain or improve the identified ecosystem services. Often, information was only available on global or African level, meaning we had to clip it to the extent of the two basins, being aware of inaccuracies that occur when scaling down global data to a more regional context. The scale of our spatial analysis is typically the sub-watersheds of 'Pfafstetter'-level 4 [Verdin and Verdin, 1999], available through the HYDROSHEDS dataset [Lehner and Grill, 2013]. However, for some more detailed analyses, several of these watershed were grouped in order to cover the full extent of important wetlands.

2. ZAMBEZI BASIN

2.1 OVERVIEW OF ECOSYSTEMS

The Zambezi basin is generally characterized by forests in the north western and croplands in the more densely populated south eastern part. Figure 1 gives an overview of the overall land cover types that are described in detail below.

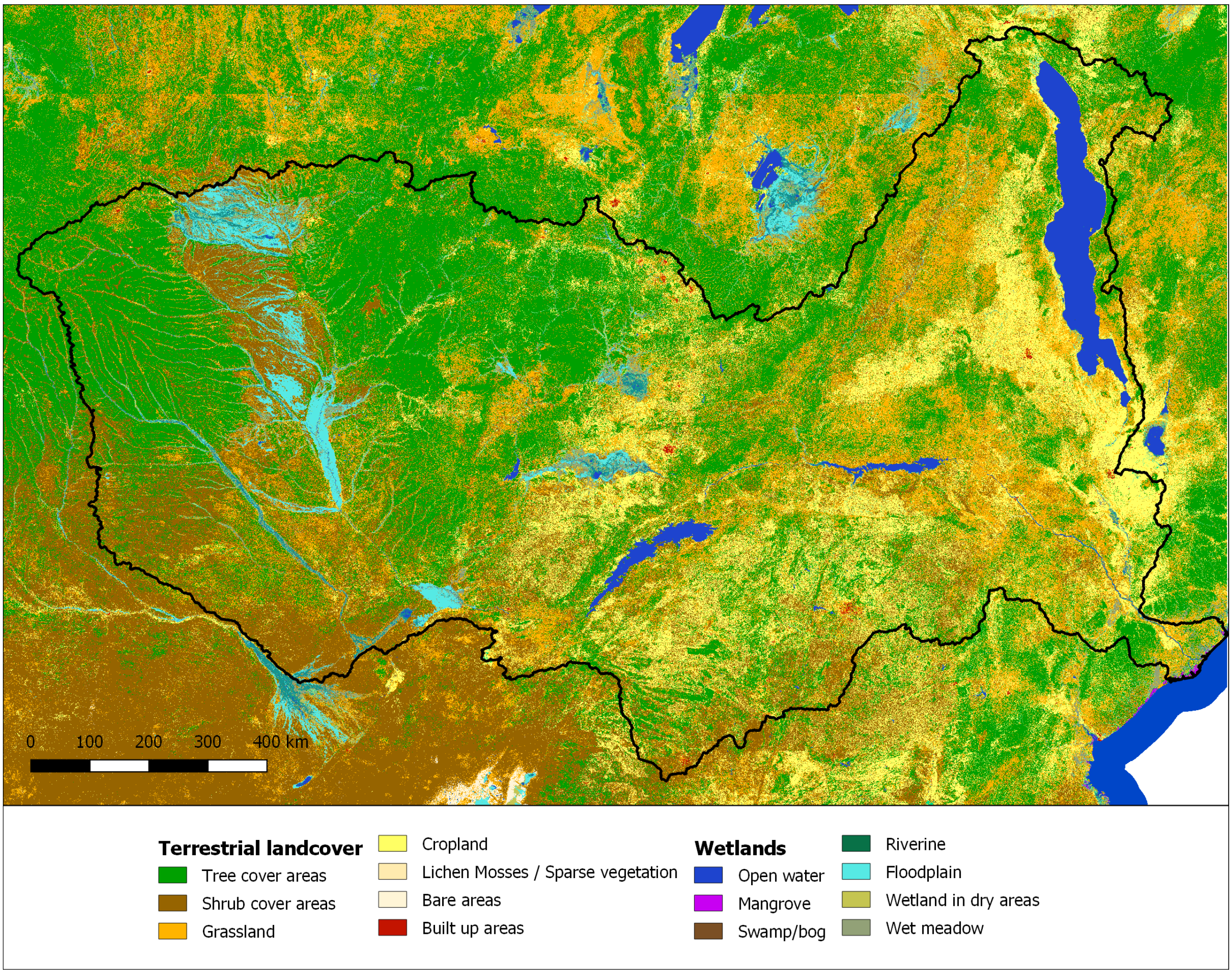


Figure 1 – Land cover classification for the Zambezi basin (Terrestrial: ESA CCI prototype African land cover map, Wetlands: T. Gumbricht, 2012)

2.1.1 Large lakes and reservoirs

Lake Malawi/Niassa/Nyasa is the largest natural lake in the ZRB, spanning a maximum length of 580 km, a width of between 16 and 80 km, a surface area of ca. 30,000 km^2 and a volume capacity of almost 8,000 km^3 [Pinay, 1988]. Laka Malawi is the second deepest lake in Africa after Lake Tanganyika and the third deepest lake in the world. The hydrological balance of the lake is dominated by rainfall which reaches 2,270 mm per annum in the lake area. Fluctuations in rainfall can lead to strong changes in lake levels. Through the Shire River the lake drains into the Zambezi [Pinay, 1988]. Lake Malawi has an estimated number of 500 haplochromine fish species of which only about five are not endemic. Fisheries around lake Malawi are of high economic value for food and the ornamental fish trade [Ogutu-Ohwayo et al., 1997]. Studies of haplochromine cichlids have been useful in understanding speciation [Salzburger et al., 2014]. The other smaller natural lakes within the Zambezi River Basin include Lake Chilwa (Malawi) and Lake Liambezi (Namibia) [ZAMCOM et al., 2015].

In contrast, Lake Kariba (Figure 1) is the largest artificial lake and reservoir in terms of water storage capacity, holding 185 km^3 of water at full supply level [ZAMCOM et al., 2015]. The other major artificial lake in the Zambezi River Basin is Cahora Bassa with a holding capacity of 55.8 km^3. These are the two main man-made lakes within the basin which jointly regulate almost 570 km of the length of the Zambezi River [Pinay, 1988]. Some of the main features of the most important lakes are given in Table 1.

Table 1 - Some of the main lake characteristic features in the ZRB [Pinay, 1988]

	Lake surface area (km^2)	**Lake Volume (10^{6}m^3)**	**Drainage Area (km^2)**
Kariba	5,250	155,000	409,600
Cahora Bassa	2,739	70,000	200,000
Itezhi Tezhi	365	5,700	106,190
Kafue Gorge	810	740	153,000
McIlwaine	26.3	250	2,200
Mazoe	0.44	30.5	645
Mwenje	0.2	13	550

2.1.2 Rivers

The Zambezi river can hydrologically be divided into three main regions [Tweddle, 2010]:

- The Upper Zambezi (from the headwaters to Victoria Falls) which is characterized by a vast inland drainage basin with little topographical relief. Rivers have merged with others through slight geological movements and this, along with a relatively flat terrain and few natural physical barriers, has allowed aquatic organisms to migrate along rivers and across floodplains through a large part of the subcontinent.
- The Middle Zambezi (from Victoria Falls all the way to Tete in Mozambique) is a highly diverse landscape that includes the Luangwa Valley, most of northern Zimbabwe, and Lake Malawi/ Niassa/Nyasa. Here, the river's biological character has been strongly shaped by the Kariba and Cahora Bassa dams.
- The Lower Zambezi (from Tete to the coast) and the lower Shire River are dominated by floodplains, channels, and shifting sandbanks with extensive grasslands, swamps, dunes, and mangroves along the coast.

Fast flowing rivers and waterfalls

The topography of the Zambezi basin is characterized by relatively flat sections in the uplands and low-lying areas in the rift valley and the coastal regions (Figure 3). The Zambezi River flows over a distance of almost 3,000 km, dropping in altitude from its source in the Kalene Hills in the north-western district of Solwezi in Zambia at 1,585 metres above sea level, to its delta where it enters the Indian Ocean 200 km north of the Mozambican port of Beira. The topography of the river basin varies in altitude from sea level at its delta to more than 1,500 metres on the plateau, with some mountainous areas rising above 2,500 metres. The plateaus are deeply dissected by the river valleys that form the tributaries of the Zambezi River, opening out into wide floodplains and plunging more than 100 metres into the gorge at the Victoria Falls, with a volume of water up to 550 million litres a minute in full flood [ZAMCOM et al., 2015]. The abrupt drop in altitude between the upland and the Zambezi and Luangwa valleys features a high number of waterfalls and fast-flowing rivers forming gorges. Victoria falls is the most prominent example (Figure 2), but almost 500 other waterfalls have been documented for touristic purposes alone in Zambia [Allen et al., 2014].

Figure 2 – Victoria Falls seen from the beginning of the Batoka gorge (image by F. Kleinschroth)

Due to the geographic limitations of hydropower to areas with contrasting topography, gorges and waterfalls are particularly affected by the construction of hydropower projects. Species adapted to gorges and waterfalls are therefore particularly threatened by hydropower projects [Lovett et al., 1997]. One example is the Kihansi spray toad (*Nectophrynoides asperginis)* that is endemic in one specific gorge in Tanzania. In 2000, a hydropower dam cut off 90% of the water coming down a waterfall, which completely changed the environment in the gorge and drove the toad to the edge of extinction [Krajick, 2006]. Another example for a disturbance sensitive species adapted to gorge environments is the Taita falcon (*Falco fasciinucha)* that nests on the cliffs of deep gorges [Dowsett et al., 2008].

2.1.3 Wetlands

A large area of the ZRB is covered by wetlands. The most notable ones being the Barotse plains, Chobe wetland, Kafue flats, Mana Pools, Lukanga Swamps and Marromeu wetlands (Figure 4). These ecosystems and their functional characteristics are strongly dependent on the seasonal dynamics of rivers. At the same time, wetlands influence basin hydrology due to their role in managing routing, storage and evaporation of water. Despite strong regional differences, the following effects of wetland on river flows have been described: i) floodplains decrease the magnitude of flood flows and increase low flows and ii) headwater wetlands increase the magnitude of flood flows and decrease low flows. [McCartney et al., 2013].

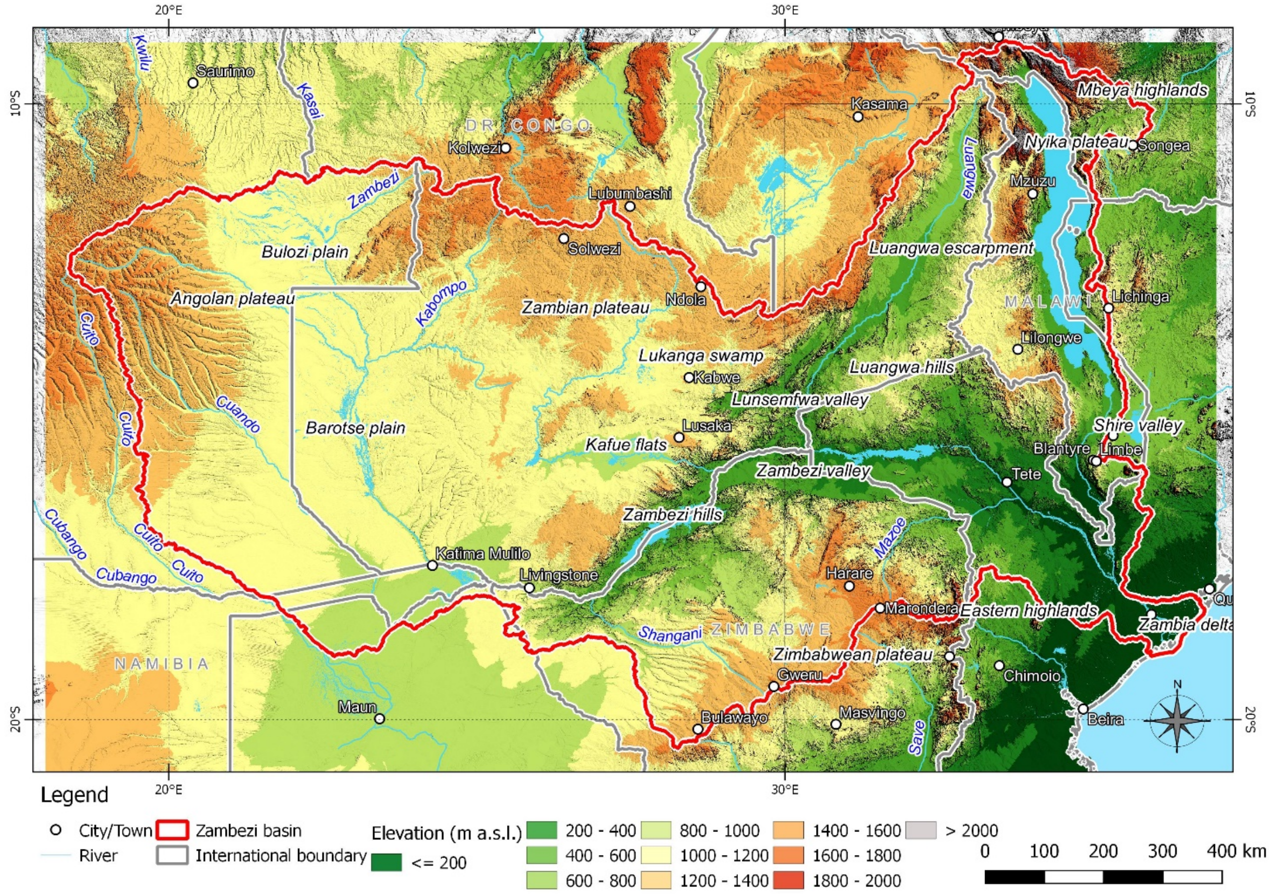


Figure 3 – Topography of the Zambezi basin (map design by Stefaan Dondeyne)

Floodplain grasslands and dambos

Dambos are seasonally waterlogged headwater grasslands (Figure 5). Globally, the northern part of the Zambezi basin is a center of occurrence for this landform [Boast, 1990]. Dambos constitute the most widespread type of edaphic grassland in the Zambezian region as they occur throughout the woodland belt in shallow depressions wherever drainage is sluggish. They are subject to seasonal flooding and parts may remain boggy throughout the year. The soil is normally acid and the vegetation forms a dense mat of grasses (*Andropogon, Hyparrhenia, Loudetia, Setaria, Trachypogon* etc.); Cyperaceae are also present in the wetter sections, where they can be dominant. [Dowsett et al., 2008]. Dambos are of high importance for biodiversity and for water supply to downstream river networks. At the same time they are very valuable sites for agriculture and grazing [Von Der Heyden and New, 2003].

The Barotse flats provide an example for a relatively intact floodplain, largely dominated by grassy vegetation. It is often assumed that the Kafue flats and also the lower parts of the Zambezi used to have similar features based on flooding dynamics before dams have been built [Zuijdgeest et al., 2015]. Due to high anthropogenic pressures, floodplain grasslands and dambos are the most threatened type of wetland ecosystems in the ZRB.

Permanent wetlands and swamps

Parts of the Chobe wetlands, the Kafue flats and the Lukanga swamps are permanently wet, providing boggy conditions which have led to the development of a peat layer [Gumbricht et al., 2017].

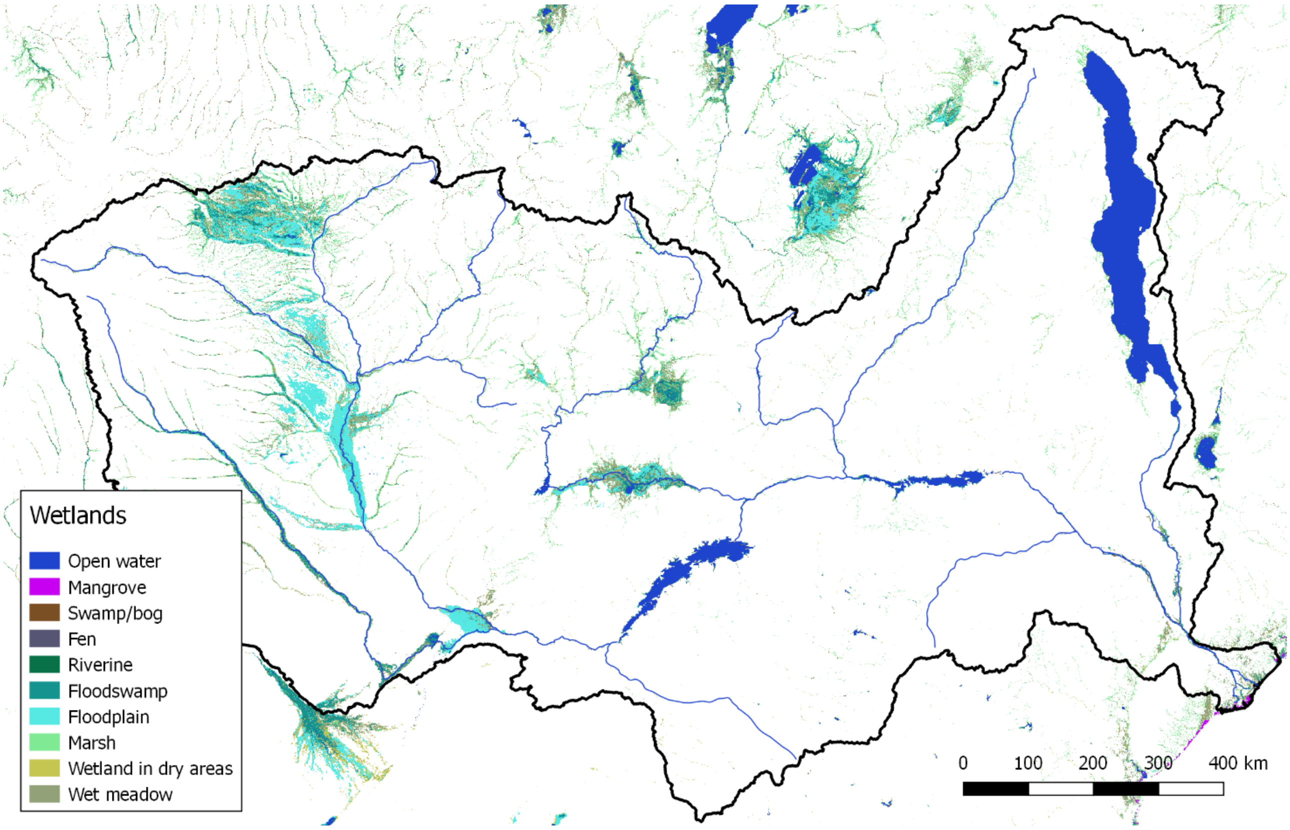


Figure 4 - Distribution of wetlands in the Zambezi basin [Gumbricht, 2012].

Figure 5 – Cultivated dambo near Mkushi in central Zambia (drone image by ATEC 3D)

Deltas

The Zambezi Delta, an IUCN Wetland Project site, is an extensive area of wetland, grassland and riparian or floodplain vegetation. In two parts, it extends in a broad triangle from Mopeia about 120 km upstream of the mouth down the Rio Cuacula to Quelimane in the north, while the southern section covers the seasonally-wet grasslands of Marromeu which extend to the sea. The Marromeu complex is a RAMSAR site, consisting of the Marromeu special reserve and several hunting concessions. Effectively, and biologically, the southern section of the delta also stretches along the base of the Cheringoma Plateau all the way to Beira. For much of this extent, however, the moisture is probably derived from seepage from the plateau and rarely from the Zambezi River [Timberlake, 1998].

Before construction of Kariba and Cahora Bassa dams, the Zambezi Delta supported a great diversity of wetland communities that were home to high concentrations of African elephant (*Loxodonta africana*), cape buffalo (*Syncerus caffer*), and waterbuck (*Kobus el/ipsipymnus*). By the time, the Delta provided important spawning grounds for fishes and critical dry-season grazing lands for domesticated livestock and wildlife [Beilfuss and Davies, 1999]. Extensive coastal mangroves and estuaries supported a lucrative prawn fishery [Gammelsrød, 1991].

A reduction of wetland areas in the Zambezi delta has led to a loss of biodiversity. The change in flow regime due to the dams and the lack of flooding in the delta has significantly impacted the Zambezi delta. Analyses of satellite images have shown that woody savanna and thicket species have increased in density and colonized far into the floodplain grassland mosaic, where the flood-tolerant species have been displaced by other drought-tolerant species. In the coastal plain, saline grassland species have displaced freshwater species and coastal mangrove has been replaced by saline grassland at the tidal margin. Sandbars have become stabilized and colonized by grassland and woody species. The abandoned alluvial channels and tributaries are undergoing a process of “terrestrialization” and the wetland area has been reducing over the last years [Beilfuss and Dos Santos, 2001].

The flood protection embankments constructed at the beginning of the 20th century have compromised the connection between the main channel of the Zambezi and the distributaries in the delta area, mainly on the Southern bank. This was aggravated by the flow regulation at upstream dams which significantly reduced the frequency of annual flood pulses. The narrow strip of mangroves that is left at the fringes of the delta is in constant decrease, supposedly because of the lack of sedimentation from the Zambezi river [Ronco et al., 2010].

A study on the landcover changes [Njati, 2014] revealed that the general trend of area under mangroves in the Zambezi delta resembles that of the global trend of mangrove reduction. The mangrove cover was reduced by 24 % with a recovery of 18 % for the 1972 - 1979 period and during the 1989 - 2013 the decline was at 14% and recovery at 26%. However the reduction takes place with different rates and in different periods for the different parts of the Zambezi Delta and is not a continuous process in all areas of the delta.

2.1.4 Forests

Most parts of the basin are covered by forests and bushland (almost 75% of the land area) [SADC/SARDC and others, 2012]. However, forest cover information varies with source both within the riparian states and at regional level [ZAMCOM et al., 2015]. Forests cover about 36% of the total land area of the Basin, ranging from 9.3% in Namibia to 56.2% in Zambia. Only a small part of the area is under exotic timber plantations, the largest area being in Zimbabwe [ZAMCOM et al., 2015]. The Zambezi Basin has diverse forest ecosystems dominated by undifferentiated Miombo and Mopane woodlands and semi-arid shrubland [White, 1983].

Undifferentiated woodlands consist of teak (*Baikiaea plurijuga*) and acacia. Other associated commercial timber species include *Pterocarpus angolensis* and *Guibourtia coleosperma*. *Baikiaea* woodland areas are found on Kalahari sands in parts of Angola, Botswana, Namibia, Zambia and

Zimbabwe. The woodland has a long history of management for commercial timber exploitation, wildlife utilization, cattle grazing and water catchment [ZAMCOM et al., 2015].

Miombo woodlands (Figure 6) are the most extensive forest type in the Basin [ZAMCOM et al., 2015]. Dominant tree species include *Brachystegia spiciformis, Julbernardia globiflora* and *Isoberlinia* found in areas with over 700mm of annual rainfall and on nutrient-poor soils. Dry Miombo dominated by *Brachystegia spiciformis*, *B. boehmii*, *Julbernardia globiflora*, and *Uapaca kirkiana* grows in areas with rainfall of less than 1000 mm, allowing a tree canopy of less than 15 metres height. In contrast, the wet Miombo occurs in areas of more than 1000 mm per year and tree canopy exceeds 15 m in height [ZAMCOM et al., 2015]. It is found in parts of Angola, the Democratic Republic of Congo, Malawi, Mozambique, Tanzania and Zambia. The dominant species are *Brachystegia floribunda, B. longiflora, J. paniculata and Isoberlinia*. Miombo woodlands hold very little merchantable timber but have a wide range of non-timber forest products that include grass, caterpillars and medicinal plants. A significant proportion of the woodland has been converted into intensive and extensive agricultural areas hence it is difficult to locate pristine woodlands [ZAMCOM et al., 2015].

Mopane woodland dominated by *Colophospermum mopane* is typical for lower lying areas with clay and nutrient-rich soils and low rainfalls (400 mm to 700 mm). This is the case in parts of Angola, Botswana, Zimbabwe, Zambia, Malawi and Mozambique [ZAMCOM et al., 2015]. Semi-arid shrubland is found in the low rainfall areas [ZAMCOM et al., 2015]. Due to water stress, it has a sparse tree canopy of 5-8 metres. Characteristic species of the wooded grassland include various Acacia (eg *Acacia erioloba* and *A. tortilis*) and *Terminalias ericea.*

Figure 6 – Miombo forest in northern Zambia. Intact remnant (left) and charcoal kiln (right). Drone images by ATEC 3D.

2.2 OVERVIEW OF ECOSYSTEM SERVICES

Ecosystem services are all kinds of benefits that humans obtain from ecosystems. This includes products/ goods and services that support human livelihoods, societies and economies. The ecosystem services concept thus links the ecosystem function with the people who benefit from them. Ecosystem services are interlinked and often interdependent. According to the Millennium Ecosystem Assessment [WRI, 2005], ecosystem services include provisioning services, regulating services, cultural services and supporting services.

2.2.1 Provisioning services

Provisioning services represent the most fundamental way in which natural ecosystems benefit people, supporting basic human needs: food, water and shelter, fuel, pharmaceuticals and fiber. Such services can be based on nutritional, material or energetic values and outputs of living systems.

Water provision

Human water needs for supply and sanitation in the ZRB was estimated at $3340 \cdot 10^6$ m^3 per year for a population of 28 million before 2000 [Shela, 2000]. This water is mostly used by the **urban** population with access to infrastructure. Overall, only 34, 35, 49 and 69 % of the **rural** population in Angola, Mozambique, Zambia and Zimbabwe respectively, have access to piped water sources [World Bank, 2010b]. Typically, water is accessed through shallow hand-dug wells in seepage zones whereas boreholes are used as substitute sources for domestic water supply. Availability of these substitutes and the distance to reach them determines whether or not householders used these boreholes for domestic water. The ZRB's population continues to grow at an average rate of about 2.36 % per annum [SADC/SARDC and others, 2012], reaching a current population estimation of more than 40 million. Consequently, the need for water will increase with the requisite increase in infrastructure development [Tumbare, 2010].

Fisheries

Fish is the main source of animal protein for the majority of **rural** communities in the ZRB, who have harvested at least 200,000 tonnes of fish per year [Shela, 2000]. Around one quarter of this fish is sourced from Lake Malawi and the Zambian part of the Zambezi River basin, respectively [Shela, 2000]. In the Zambian part of the ZRB, Lake Kariba has become the main fishing ground, mostly due to the introduction of the small, but highly productive Kapenta sardine. All other regions are in decline, including those that used to have abundant fish stocks such as the Kafue river and the Upper Zambezi (Figure 7). Fisheries provide an important source of employment and income. The subsector contributes about 3.2% to national GDP. Current estimates for Zambia indicate that over 500 000 persons directly or indirectly obtain part of their income from the fisheries sector. By 2014, about 80 826 tons of fish have been caught in Zambia alone [Department of Fisheries Zambia, 2015].

Subsistence fisheries are mainly on floodplains and exploit natural seasonal cycles whereas man-made reservoirs are the focus of commercial fisheries. Seasonal flooding is a major driver of ecological transformation and fisheries productivity in the Zambezi River Basin [Junk et al., 1989]. Fish species migrate onto floodplains to breed during the first floods in November/December. Spawning on the floodplains offers juveniles abundant food, well-oxygenated environments and greater security from predation. Therefore, natural flood pulses contribute considerably to fish production in the basin [M. McCartney and Nyambe, 2017]. The operation of existing and planned dams negatively impacts such flood dynamics and thus fish populations.

Due to unsustainable fishing practices, fish stocks in the whole Zambezi river system, except Kariba, have declined in terms of catch rates and the loss of larger, most valuable fish species [Tweddle et al., 2015]. Especially for the Kafue river, this decline can be linked to the start of the dam operations in the late 1970's. Only parts of the losses in catch were compensated by fishing grounds in the new Itezhi-Tezhi reservoir (Figure 7).

Flood recession agriculture

Within the ZRB, our own spatial analysis showed that up to 15 000 km^2 of wetlands are potentially used for agriculture Table 2). Of this area, 1130 km^2 in the main wetlands are confirmed by World Bank (2010a, Table 3). Flood recession agriculture is a major contributor to agricultural production in some sub-basins and surpasses the area equipped for formal irrigation in countries such as Zambia, Namibia, Botswana and Mozambique. Additionally, cultivation in dambos is widespread. Dambos are widely exploited as alternative, or complement, to rain-fed agriculture. The intensity of cultivation varies much, such as in Zimbabwe where between 5 – 75 percent of the dambo area is cultivated [McCartney et al., 1997]. The Caprivi floodplain consists of clay-rich soils combined with a good flooding regime and nutrient balance. Crops grown include maize on the wetter floodplain areas as floodwaters retreat, and millet and sorghum on drier lands. Other minor crops grown are potatoes, vegetables, beans and other legumes, pumpkin, melons, and groundnuts [World Bank, 2010a].

Before the construction of Kariba and especially Cahora Bassa dams, flood recession agriculture used to be widespread in the Zambezi delta [Beilfuss and Davies, 1999]. Strong reductions in flooding dynamics throughout major wetlands in the Zambezi basin have reduced the extent of this agricultural practice. Yet, our observations near the **urban** areas of Mkushi in the Lunsemfwa catchment (Figure 8) and near Kafue town show that temporarily flooded areas still have an important role across the catchment (Figure 9).

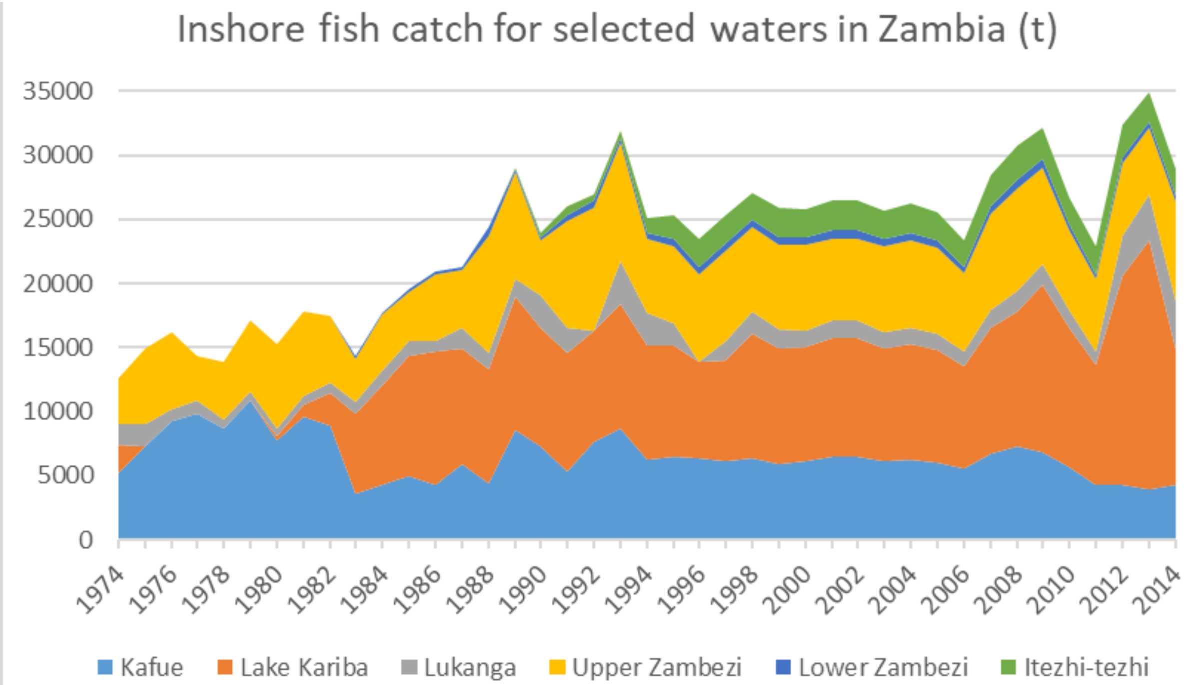


Figure 7 – Fish catch in selected waters of the Zambian part of the Zambezi basin [Department of Fisheries Zambia, 2015]

Table 2 – Results of a basin wide spatial analysis to determine overlaps between potentially cultivated areas (DAFNE D3.3) and different types of wetlands in the ZRB [Gumbricht et al., 2017].

Wetland type	**Open water**	**Mangrove**	**Swamp/ bog**	**Riverine**	**Flood-swamp**	**Flood-plain**	**Marsh**	**Wetland in dry areas**	**Wet meadow**
Crop area (km^2)	754	10	463	18	1126	2320	7091	666	2899

Table 3 – Main flood recession agriculture areas in the Zambezi River Basin (hectares) [Source: World Bank, 2010a]

Name of the floodplain	**River**	**Country**	**Floodplain area (ha)**	**Recession area (ha)**
Barotse Floodplain	Zambezi	Zambia	900,000	28,000
Caprivi-Chobe Lake Liambezi floodplain	Cuando/Chobe	Namibia, Botswana	220,000	9,000
Kafue Flats	Kafue	Zambia	650,000	13,000
Luangwa Valley Floodplain	Luangwa	Zambia	1,080,000	17,000
Lower Shire Floodplain	Shire	Malawi	1,510,000	21,000
Zambezi Delta Floodplain	Zambezi	Mozambique	1,940,000	25,000
Total			6,300,000	113,000

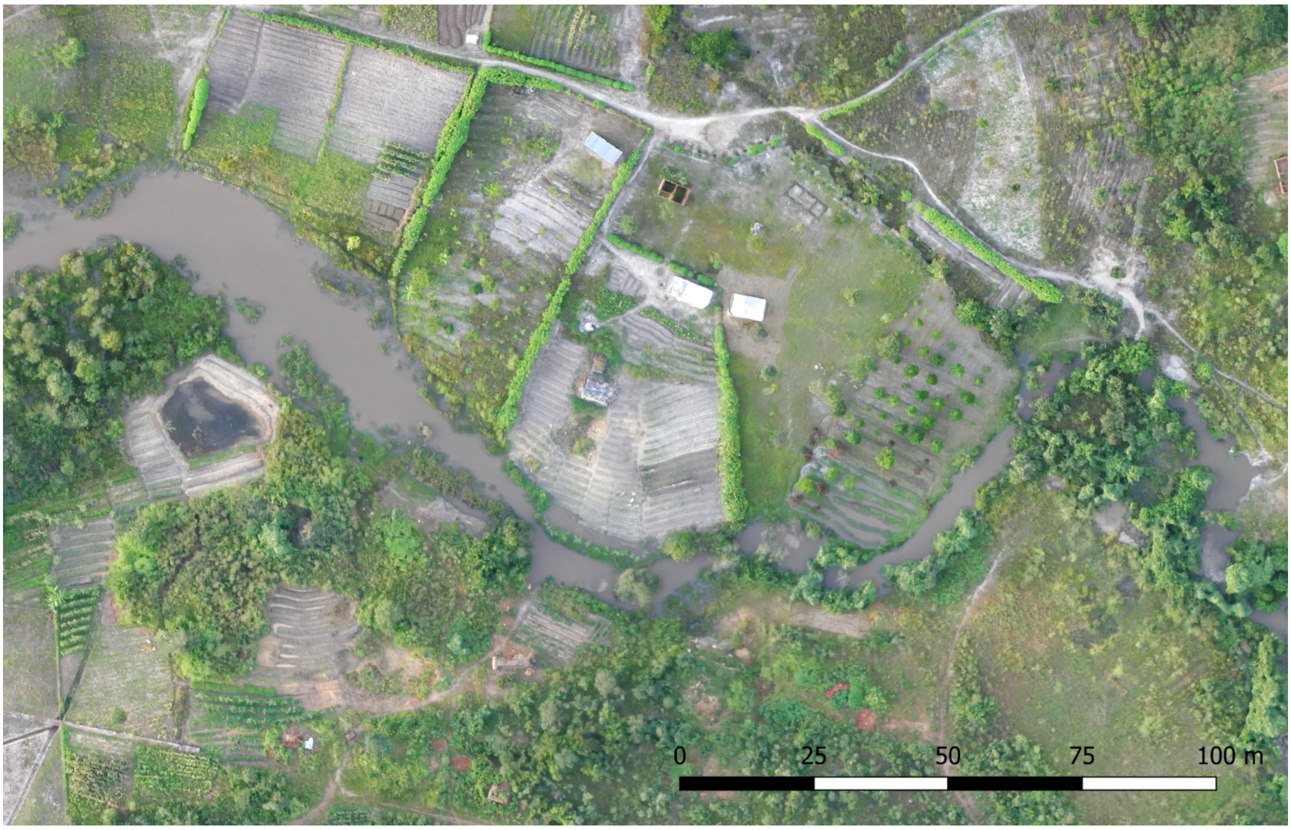


Figure 8 – Partially flooded fields along the Chibefwe river near Mkushi in northern Zambia (drone image by ATEC 3D)

Figure 9 – Small-scale agricultural areas in the riparian area of the Kafue river near Kafue town (Drone image by ATEC 3D)

Livestock grazing

Livestock grazing is an important economic activity for many people in the Zambezi basin [McCartney and Nyambe, 2017]. Nomadic pastoralism is a key economic activity for many **rural** communities in the ZRB. In 2011 the head of cattle was estimated to be around 41 million [ZAMCOM et al., 2015]. Transhumance is very common, with herds being moved to floodplains in the dry season and higher areas in the wet season (Table 4). In the Barotse floodplains, cattle are moved onto the floodplain starting around June, with all cattle on the floodplain between August and December whereas most cattle are on the higher ground from February to May, which is a time of stress and high mortality due to the reduced quality of pasture [World Bank, 2010a]. In the eastern Chobe-Caprivi Wetlands, floodplain grasslands are home to about 124,000 cattle, a third of which are moved to higher ground during the peak flood season (March to June). The value of cattle on the floodplain is typically milk and plowing. Additionally, cattle are a vital source of wealth providing owners with a drought-coping strategy, access to community rights, as well as other intangible traditional benefits [World Bank, 2010a].

Table 4 - Cattle grazing in the major wetlands of the Zambezi River Basin

Wetland	**Dry-season head of cattle**	**Estimated financial gross value (10^6 USD)**
Barotse	435,000[1]	3.32[1]
Kafue Flats	250,000[2]	4.0[2]
Caprivi Floodplain	124,000[1]	1.94[1]
Lower Shire Floodplain	104,450[1]	1.77[1]
Luangwa	N/A	0.90[1]
Lukanga	Unknown	N/A
Zambezi Delta	0	0

[1][World Bank, 2010a]; [2][Seyam et al., 2001]

Forest products

Forest products provide for basic needs such as food, shelter and health. Wild foods include fruits, honey, vegetables, mushrooms, leaves, roots as well as some insects such as caterpillars and meat from wild animals like buffalos, warthog, impalas, antelopes, hares, birds and mice. These wild foods are significant for food security and nutritional purposes [Clarke et al., 1996]. Additionally, fuel wood is used for cooking and lighting, and in some rural industries such as brick-making, lime production, smoking fish, brewing beer and the drying of tea and tobacco [ZAMCOM et al., 2015]. As regards shelter, important products include poles and construction materials. Trees in miombo woodlands also offer a range of tanins, dyes, oils, resins and gums that are used for a wide range of purposes [Clarke et al., 1996].

2.2.2 Regulating Services

Regulating ecosystem services include climate regulation, controlling the hydrological flows of water, water purification, soil erosion control and providing a habitat for pollinators [WRI, 2005]. By regulating biophysical phases and processes, natural ecosystems make a vital contribution to occupations and economic development through the prevention and alleviation of damage that inflicts costs on society [Carpenter and Folke, 2006].

Water purification

The major ecosystems (e.g., wetlands, forests and woodlands) in the two basins influence the micro and regional climate by controlling evapotranspiration and precipitation, and regulate hydrological flows with groundwater recharge [Gichuki et al., 2001]. Wetland vegetation purifies water by uptaking nitrates, phosphates and toxins from the water flowing through, thereby lowering the nutrient load. This role can change over time as wetland plants grow and die [Verhoeven et al., 2006]. This function is important in the upstream areas of basin's that are exposed to considerable non-point source pollution from the use of agrochemicals [Lalah et al., 2003]. Wetlands, especially dambos, may also play an important role in mitigating the health risk resulting from water pollution from copper mining in the ZRB [Schumaker, 2008].

Flow and flood regulation

Soils and vegetation have an important role in hydrology by regulating transpiration and evaporation thereby regulating water channeling and storage [Blumenfeld et al., 2009]. Ecosystems reduce frequency and damaging impacts of floods while simultaneously ensuring that water is available thereby benefiting human populations downstream. The major ecosystems in the basins. such as forest, woodlands and wetlands, help to slow the speed of floodwaters thereby limiting the detrimental effects of floods and controlling soil erosion [Uluocha and Okeke, 2004].

Carbon storage

Major ecosystems in the basins store carbon in the long and short-term. For example, carbon is stored in wetland sediments over the long term as peat and over short term in biomass, especially in forests. The level of carbon storage in the different ecosystems such as wetlands and forest ecosystems is determined by several factors that include the wetland type, forest vegetation composition, and climatic and hydrologic variables.

The ZRB with its' extensive coverage of dry forests and large wetlands has an important potential for carbon sequestration (Figure 10, Table 5, McCartney and Nyambe, 2017). Total amounts of carbon sequestration and fluxes through wetlands and other ecosystems are difficult to determine, but one existing estimate of net present value from carbon sequestration in four wetlands of the ZRB is around 110 million USD [Turpie et al., 1999]. Yet, the ZRB is also a hotspot of deforestation [Hansen et al., 2013] and forest degradation [Chidumayo, 2013] with conversion of forest to agriculture and charcoal production releasing large amounts of carbon to the atmosphere.

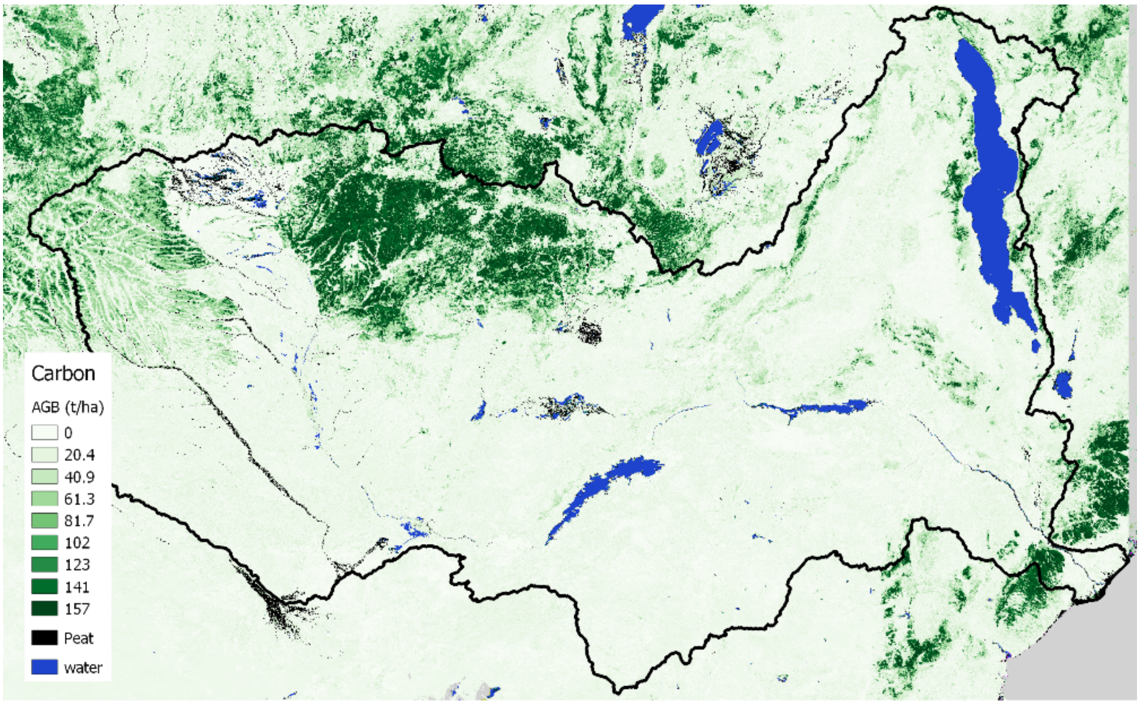


Figure 10 – Carbon storage in the Zambezi basin. AGB=Above ground biomass [Avitabile et al., 2016], Peat = presence of peatlands, water = Seasonal or permanent surface waters [Gumbricht, 2012]

Table 5 - Rough estimates of the NPV (net present value, US$) of the carbon sequestration function of four wetlands in the Zambezi basin. Values based upon an average of two tons of carbon removed per hectare per year (Source: Turpie et al., 1999).

	Barotse plains	**Chobe-Caprivi**	**Lower Shire**	**Zambezi Delta**
NPV of carbon sequestration	27 million	11 million	8 million	64 million

Buffering of species invasions

Free-floating species such as Water Hyacinth (*Eichhornia crassipes*), Water Lettuce (*Pistia stratiotes*), Red Water Fern (*Azolla filiculoides*), and Kariba Weed (*Salvinia molesta*) are common throughout the Zambezi River Basin. In standing and slow flowing waters with high nutrient contents, especially Water hyacinths can become extremely dominant, with negative effects on fisheries, hydropower generation and water quality. The plant can double its mass every four days under warm eutrophic conditions. Evaporation through the leaves of the plant has been shown to be 150% higher than an open water surface [Lallana et al., 1987], the species therefore increases water losses from reservoirs to the atmosphere. The proliferation of these invasive plants poses navigational and operational problems for hydropower production if the weeds get into the hydropower or domestic water supply intake [ZAMCOM et al., 2015].

Streamflow and water quality are the main factors controlling the growth of water hyacinths and therefore play an active role in buffering their invasions. This information should be actively taken into account for water management decisions, as outlined in DAFNE Deliverable D4.2 Models of Environmental Policy in the Omo and Turkana basins (https://polybox.ethz.ch/index.php/f/951413617)

Disease control

Seasonal fluctuations in lake levels can reduce breeding of mosquitoes that are malaria vectors [Lautze and Kirshen, 2007]. Around the Koka Reservoir in Ethiopia, findings suggest more rapid drawdown of reservoir water levels during the peak malaria season can contribute to reduced disease transmission [Kibret et al., 2009]. Around the Kariba reservoir in Zimbabwe-Zambia, preliminary evidence suggests that lowered water levels at key times in the year may reduce malaria transmission [Bianchi et al., 2018]

2.2.3 Cultural Services

Tourism

Tourism in Southern and Eastern Africa depends largely on the rich biodiversity of the region/area. In 2007, the annual direct value of tourism in the Zambezi River Basin was approximately USD 457 million, representing between 12 and 20 percent of the tourism economy of the riparian countries. The contribution of the tourism industry to the gross domestic product is around 10% for Zimbabwe and 6% for Zambia [World Bank, 2010a]. The total contribution of tourism to the economy varies substantially between riparian countries. In Angola, for example, very few tourists visit the Zambezi River Basin, whereas in Zambia it is estimated that 54 % of tourists visit the Victoria Falls and 34 % experience game viewing, adventure activities, sport fishing and hunting. By and large, the Caprivi-Chobe-Kasane-Victoria Falls area is the most significant tourism destination in the Zambezi River Basin [World Bank, 2010a].

Social systems

Social systems cover all non-material, intangible and normally non-consumptive outputs of ecosystems that affect physical and mental states of people. Several communities in the Zambezi River Basin have different customs, rituals and philosophies, aligned with the natural rhythms of forest and wetland ecosystems that provide a sense of place to people [M. McCartney and Nyambe, 2017].

2.2.4 Supporting Services

One of the important supporting services that is associated with natural systems such as wetlands is soil formation. This primarily results from the comingling of decomposing organic material with weathering rock [Costanza et al., 1997], mineral matter and sediment. The profiles of these soils vary depending on whether these occur in the wetland itself, on the wetland fringes, in the transition zone to dryland or the dryland with the former two being more amenable to hydric soil indicators [Vepraskas et al., 1999]. Wetland vegetation also traps and retains sediments transported by runoff and in so doing, controls siltation downstream [Haycock et al., 1997]. Another vital supporting service that the basin's natural systems (e.g., forest and woodlands) provide is nutrient recycling [Aerts et al., 1999].

2.3 HUMAN DEMAND FOR ECOSYSTEM SERVICES

Ecosystem services are often seen as an economic factor that can be described as a supply-demand relationship. Yet, different than for a manufactured product or a typical service, is the supply independent from the demand (except if unsustainable uses leads to deterioration of the ecosystem). The demand for ecosystem services is spatially highly variable and can - depending on type - range from local to global scale [Syrbe and Grunewald, 2017]. Monetary calculations of ecosystem services are useful as a communication tool for certain target groups of decision makers [Nelson et al., 2009], but the tradeable value depends on the money that people are actually willing to pay for them. A very conservative estimate of the value of all ecosystem services in the ZRB is ca. 1.5 billion US$ a year [M. McCartney and Nyambe, 2017]. These estimates are based on examples from the literature, as summarized in chapter 2.2. A more general analysis of the economic situation within the different countries and an econometric model of water use across the Zambezi basin is given in DAFNE Deliverable D4.1 – Models of economic development in the Zambezi river basin (https://polybox.ethz.ch/index.php/f/871397242).

2.3.1 Rural areas

In this study, we focus on ecosystem services of free-flowing rivers (in contrast to services by built infrastructure, such as irrigation agriculture and hydropower). We suggest that demand for ecosystem services of free-flowing rivers increases with population density but the services that are valued the most switch with urbanization and industrial development as urban populations and industry are expected to have higher demand for ecosystem services of regulated rivers. Rural populations depend to a much higher degree on the direct provision of ecosystem services as they are less connected to infrastructure networks and do not have sufficient financial resources e.g. to buy food produced elsewhere. We combined annual maps (2000 to 2018) of population-density with detected presence and absence of night-lights from satellite imagery (OLS DMSP, VIIRS), as an indicator for electrification and industrial activity. This allowed us to classify the land surface into four groups: A1 - low population (< 5 people per km^2) and no night-lights; A2 - higher population and no night-lights; B1 - low population and night-lights; B2 - higher population and night-lights. We defined shifts to the B2 category as a sign of urbanization. We found that the A1 category (largely uninhabited areas) and the A2 category (rural areas) remained relatively stable in size over time. The B2 category (urbanized areas) increased. The B1 category (areas with night lights and low population) was almost absent in the basin (Figure 11). This shows that despite urbanization, large parts of the population remain without access to electricity and industrial labour and continue to depend on ecosystem services in their vicinity.

2.3.2 Urban areas

The most important urban centres in the ZRB are Harare, Lilongwe, Blantyre, Lusaka and Kitwe (together with other copper belt towns). All of them have grown over the past decades due to rural-urban migration (Figure 12). Typically, urban areas do not have the same spatial link with the area where an ecosystem service is provided, as transport and storage of agricultural products, more constant supply of electricity and generally access to infrastructures allow for tele-connectivity between the place a service is sourced and where it is demanded. While the demand for food, water and energy in urban areas is increasingly covered by more industrialized activities, close links from rural to urban areas are often maintained. Through these more informal channels, forest products such as charcoal and timber, agricultural produce, fish and bushmeat find their ways to urban areas.

With growing urbanization and the development of megacities, the planning and valuation of urban ecosystem services gains in importance [du Toit et al., 2018]. Especially “green infrastructure” such as parks, urban forests and wetlands provide many of the provisioning ecosystem services mentioned, including food (through urban agriculture), energy (firewood, etc.) and recreation [Cilliers et al., 2013]. Additionally, urban green areas help with regulating the micro-climate, support groundwater storage by collecting water run-off from sealed surfaces and provide a filtering function for polluted and eutrophicated surface waters. Given widely unplanned city development, cities like Lusaka are particularly in need of improved green infrastructure [Simwanda & Murayama, 2018].

2.4 CHANGING AVAILABILITY OF ECOSYSTEM SERVICES

2.4.1 Water Availability

Dams lead to upstream impoundment and downstream equalization of flows. This influences ecosystems in several ways:

- Changed timing of water availability. Water from turbines is available year-round, while flood peaks are removed, leading to a reduction in seasonally inundated areas.
- Equalization of annual flows leads to reduction of seasonally flooded areas and increase in permanent waterbodies [Mumba and Thompson, 2005]
- New standing water bodies and abstractions for irrigation can have higher losses through evaporation, leading to reduced amounts of water available downstream
- An overall reduction in flow-speed favours a different set of fish species
- In-stream connectivity is directly interrupted by dams, but also by reduced peak flows that allow fish to migrate into floodplains and upstream river areas.

Expected effects of a reduction in seasonal water availability dynamics:

- Dieback of vegetation adapted to seasonal flooding (riparian forests, grasslands)
- Lacking trigger for annual upstream fish migration and loss of spawning habitat
- Flood recession agriculture will not be possible anymore
- Shallow lake areas remain either permanently dry or inundated
- Intensified grazing in areas which no longer flood can exacerbate degradation
- Reduced dynamics in river morphology leading to loss of disturbance-dependent delta habitats
- If flooding is reduced there may be less evaporation from the floodplain. This would effectively increase the volume of available water.

Surface Water Dynamics

Seasonal and permanent availability of surface water influence several ecosystem services described above. The most important values of floods due to seasonal fluctuations in surface waters are that they provide spawning habitats for fishes and water and nutrients for agriculture.

We used a global surface water time series based on Landsat images [Pekel et al., 2016] to determine long-term changes in the overall surface water extent within the two basins (Figure 13). We found that for the ZRB, surface waters in both the Barotse plains as well as the Delta have been overall stable between 1984 and 2015 (despite local differences), while the Kafue flats showed an overall increase over time(Figure 14). This can be associated with increased environmental flow releases between 2007 and 2013 (see Figure 26).

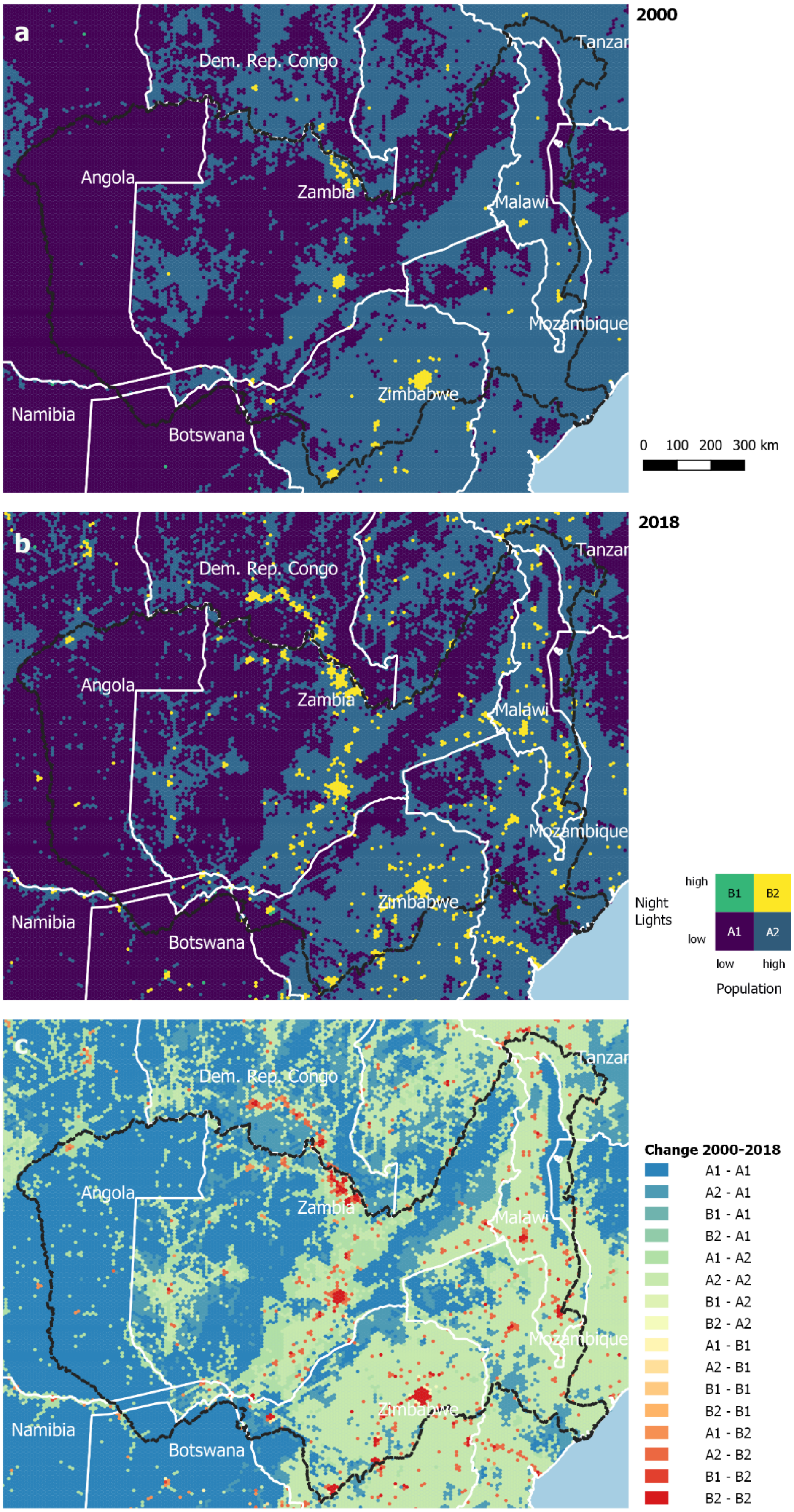


Figure 11 – Distribution of rural (A2) and urban (B2) population in the ZRB as determinants for direct and indirect demand of riverine ecosystem services, comparing 2000 (a) and 2018 (b) and the changes between classes in those years (c). Night lights are based on DMSP OLS and VIIRS satellite imagery, population is based on [Rose et al., 2018].

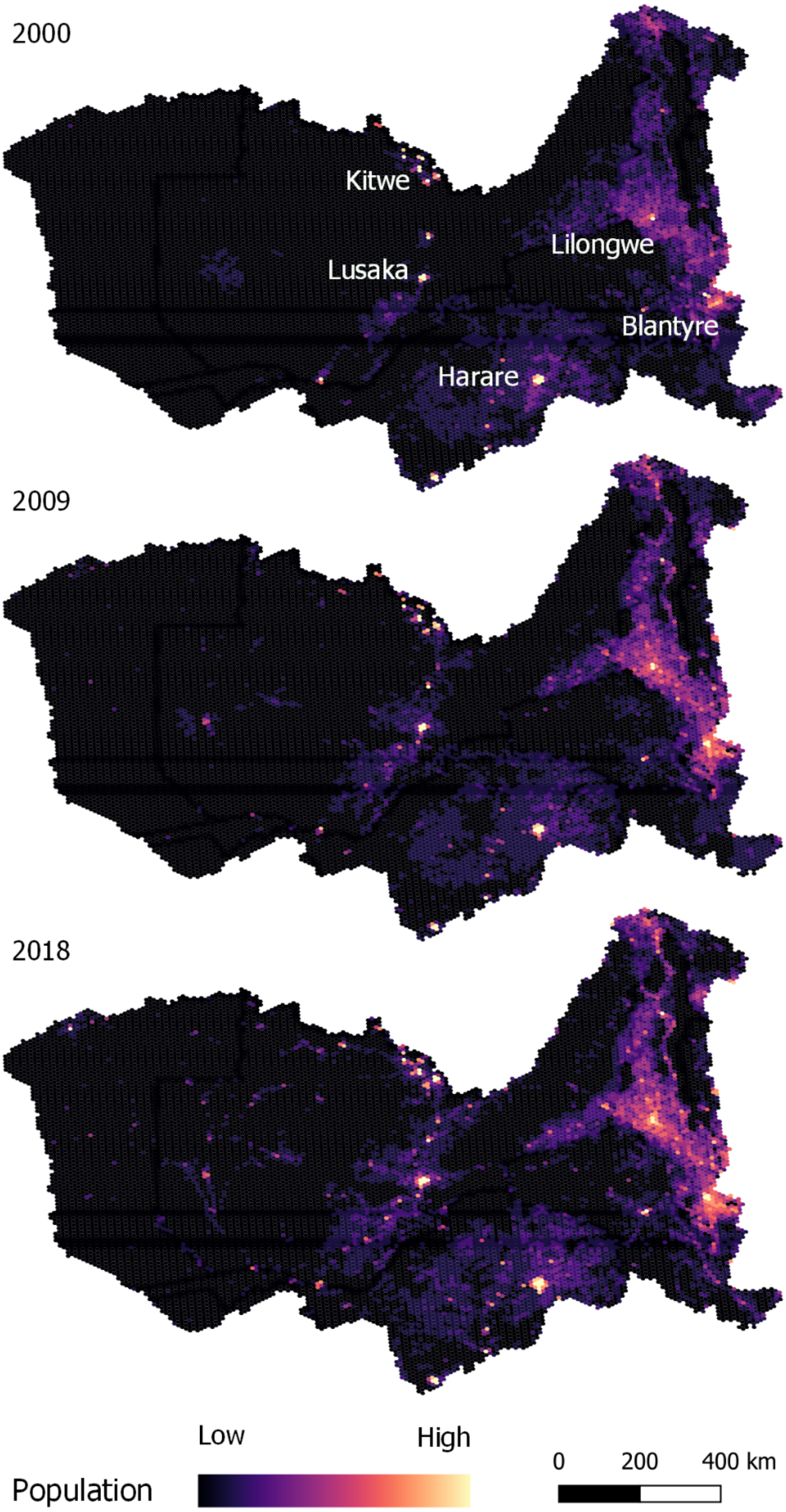


Figure 12 – Population distribution across the Zambezi basin in 2000, 2009 and 2018 [Rose et al., 2018].

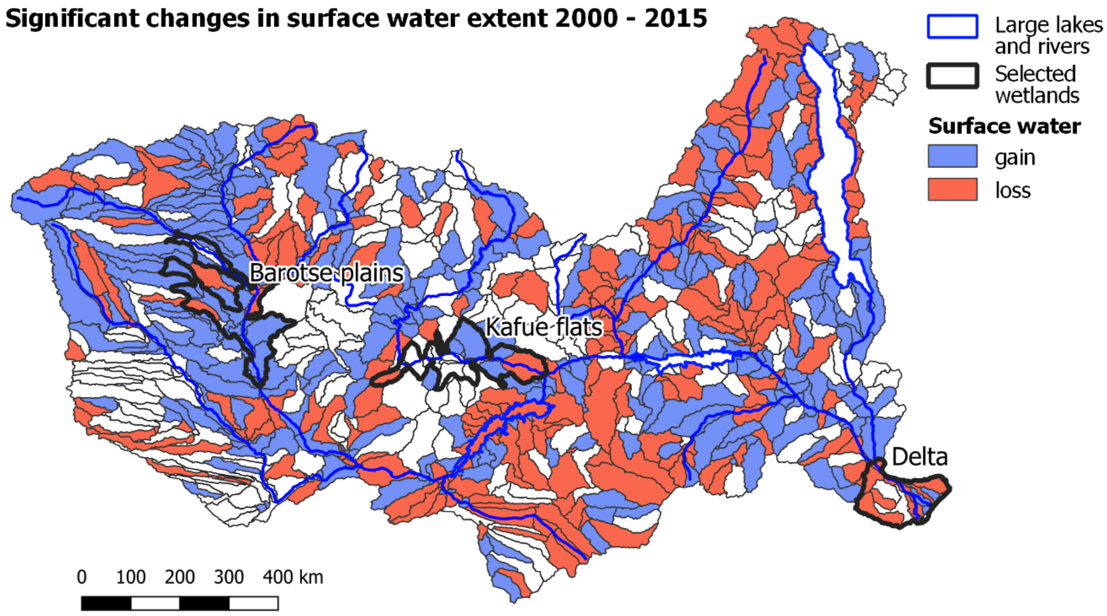


Figure 13 - Changes in surface water extent between 2000 and 2015 [Pekel et al., 2016] based on slope estimates of linear regressions (water area against time). Only significant (P < 0.01) results are shown, others are left white. See Figure 14 for the entire time sequence of the highlighted wetlands.

2.4.2 Water Quality

Aquatic ecosystems are strongly influenced by the biotic and abiotic conditions of the water such as temperature, turbidity and chemical composition such as nutrient loads. For example, nutrient inputs from agriculture and industry influence the species composition in rivers and lakes. Such eutrophication increases the growth of invasive aquatic weeds like water hyacinth which impact negatively on the utilisation of the water body. Another form of pollution can be the release of cold, anoxic water from lower stratums of reservoirs at dams, which strongly changes the thermal regime of warm tropical rivers and potentially affects fish and other organisms adapted to a certain temperature range [Olden and Naiman, 2010]. A detailed overview of the role of anthropic forcing on water quality is given in DAFNE deliverables D3.2 and D 3.6: Water quality response in the Zambezi and Omo rivers to reservoir management scenarios (https://polybox.ethz.ch/index.php/f/867227668).

Floating vegetation invasions as a symptom of water pollution

The mass coverage of water bodies by floating vegetation has been described as “a symptom of our failure to manage our resources” [Holm et al., 1969] and is therefore an important indicator for the health of aquatic ecosystems.

The Kafue gorge reservoir in the ZRB is known to trap large amounts of floating vegetation such as the invasive water hyacinth. This causes high costs for filtering and removal at the hydropower station, obstructs boat traffic and negatively affects water quality. We are therefore proposing to include the control of floating vegetation as an important component of environmental flow regimes as outlined in DAFNE Deliverable D4.2 Models of Environmental Policy in the Omo and Turkana basins (https://polybox.ethz.ch/index.php/f/951413617)

We linked available discharge data from the Kafue river with remotely sensed coverage by floating vegetation to illustrate the link between flow regimes and species invasions (Figure 15). Our bimonthly time series from Landsat images show seasonal and long-term fluctuations. Throughout the 1990’s, the Kafue gorge dam had continuously low peaks in discharge, allowing dense mats of floating vegetation to dominate throughout the year (Figure 16). This spell was only broken by an extremely high water event in 2001, when large amounts of water were released at the dam.

According to the Kafue River Trust, the water hyacinth problem at the Kafue was solved after closing the fertilizer plant Nitrogen Chemicals of Zambia in Kafue town and introducing pollution control measures at Zambia Sugar and Kafue Fisheries (http://www.kafuerivertrust.org/invasive-alien-species/). Yet, our own observations have shown that the fertilizer plant is currently operating. This corresponds with higher densities of floating vegetation since 2011.

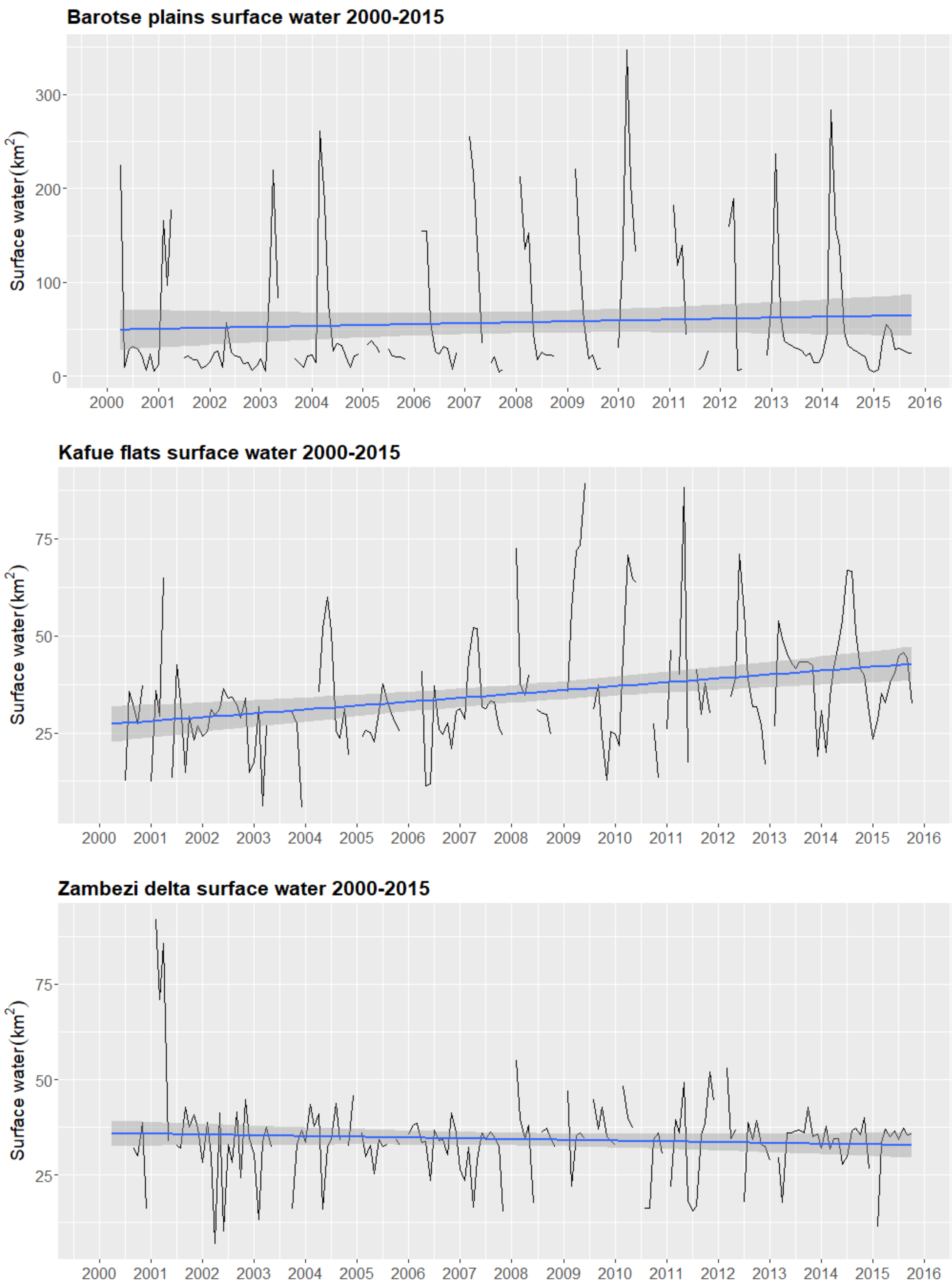


Figure 14 - Surface water extent in three selected wetlands (location see Figure 13) between 2000 and 2015.

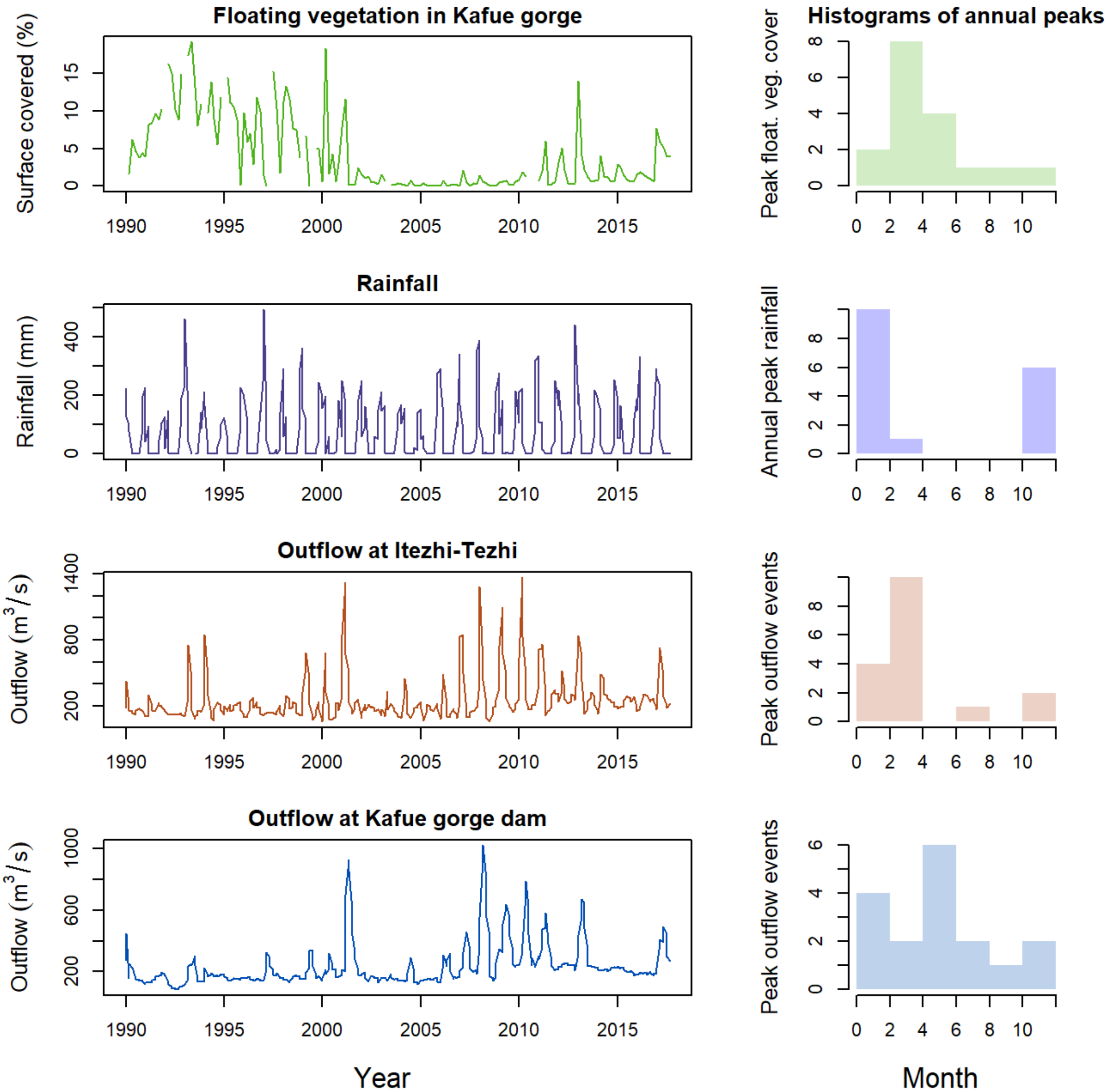


Figure 15 – Hydrographs of the Itezhi-Tezhi and the Kafue gorge dams (first two graphs, source:ZESCO) compared with the area coverage of floating vegetation between Kafue town and Kafue gorge dam (see Figure 16) as determined from a classification of bi-monthly mosaics of Landsat 5, 7 and 8 images (codes written by VISTA in Google Earth Engine).

2.4.3 Sediment Transport

Dams are well known to trap sediment and water released at dams typically has low levels of dissolved particles, oxygen and nutrients. Wherever erosion rates are increased due to deforestation in upstream areas, siltation of dams can become a serious problem to hydropower production due to reduced reservoir volumes. The consequence for downstream ecosystems is “sediment starvation”. Even if flow peaks are maintained, for example as part of environmental flow measures, sediment deposition in floodplains and deltas will be strongly reduced. This leads to a decrease in fertility of agricultural land, affecting people who cannot afford artificial fertilizers. Also aquatic and riparian species depend on regular inputs of fresh nutrients and sediment as food and habitat. It has been shown that sediment-poor water in rivers, increases erosion rates in the river bed and during over bank flow. These “hungry rivers” lead to additional negative downstream effects [Kondolf, 1997].

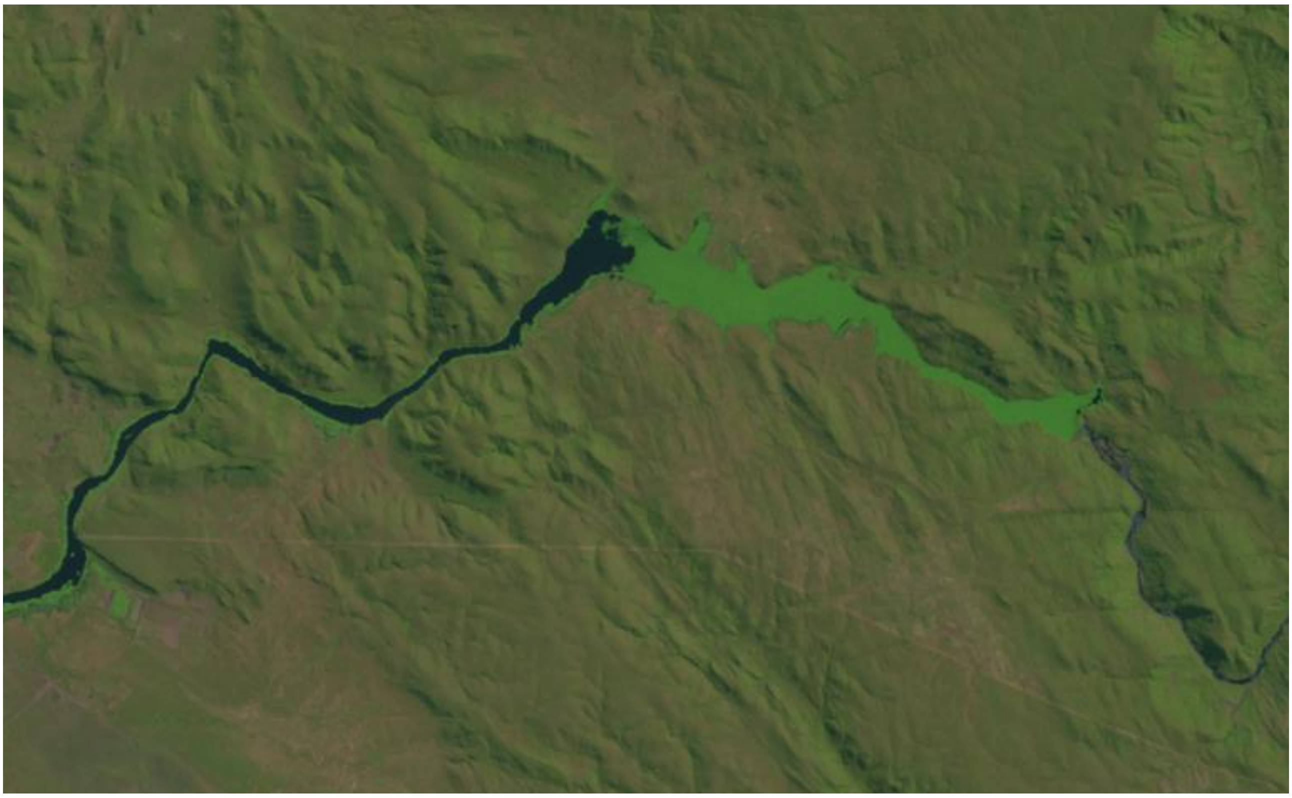


Figure 16 – The Kafue gorge reservoir on a Landsat 5 ETM image from 05/12/1993

2.4.4 Forest and Land Cover Change

Deforestation in the Zambezi basin is not distributed equally. The Zambian part of the basin is leading the statistics with more than 5% of the land surface being permanently deforested between 2000 and 2012. Less than 1% of these 12106 km^2 regained tree cover again. Other countries with relatively high deforestation rates are Mozambique, Tanzania and Malawi while Botswana, Namibia and Zimbabwe had relatively low values (Table 6). High expansion rates of commodity crops might be one of the main drivers of deforestation, at least in Zambia and Tanzania [Ordway et al., 2017].

An anthropogenic effect on forests that is directly linked to water availability is the dieback and change in species composition in riparian forests due to shift in flood occurrence [Stave et al., 2005]. The lack of *Faidherbia albida* establishment on the Middle Zambezi floodplains was linked to the decreased occurrence of Flooding events, associated with a decrease in alluvial deposits, soil moisture and groundwater recharge [Gope et al., 2015; Ncube et al., 2013].

An adverse effect is the encroachment of bushlands into grasslands, which might mostly be linked to increased grazing density and duration and changes in burning patterns [Gil-Romera et al., 2011].

Table 6 – Tree cover loss and gain between 2000 and 2012 for the portion of each country overlapping with the Zambezi basin (values extracted with Google Earth Engine from Hansen et al., 2013).

	Loss 2000-12 (km^2)	Gain 2000-12 (km^2)	Gain (%)	Total area (km^2)	Net loss 2000-12 (%)	Loss 2012-17 (km^2)
Angola	2180.48	29.49	1.35	256682	0.84	832.34
Botswana	12.19	0.12	0.96	17318	0.07	0.40
Malawi	1786.19	99.38	5.56	169317	1.00	691.10

Mozambique	3724.07	67.36	1.81	112650	3.25	1453.43
Tanzania	809.82	144.73	17.87	17334	3.84	406.53
Namibia	36.97	0.17	0.46	27955	0.13	6.85
Zimbabwe	2499.93	58.83	2.35	582619	0.42	684.26
Zambia	12106.39	105.88	0.87	214111	5.60	5258.63

We used land use change analysis based on global land cover maps from the ESA CCI (http://maps.elie.ucl.ac.be/CCI/viewer/index.php, Li et al., 2017) to highlight hotspot areas of change (Figure 17) and to show the proportion of transitions between different land cover classes from 1992 to 2015 (Table 7, Figure 17) [Moulds et al., 2015]. We show that major land use changes occurred in those areas with the highest density of **rural** population (see Figure 11) such as around Lake Malawi. These changes are likely to be linked with agricultural conversion and un-sustainable forest uses, often described as the most important drivers of change in the Zambezi basin. The direct comparison of transitions shows an increase of 12% for cropland and a loss of 3% in forest cover (Table 7). Other important gains in land cover were **urban** (100% increase), wet (8%) and bare lands (6%). This, however, did not affect the overall dominance of the Zambezi basin by forested ecosystems (Figure 18).

In contrary, we show that with increasing **urbanization**, electrification and industrialization (as indicated through night lights from satellites), forest cover overall increased, despite population growth (Figure 44).

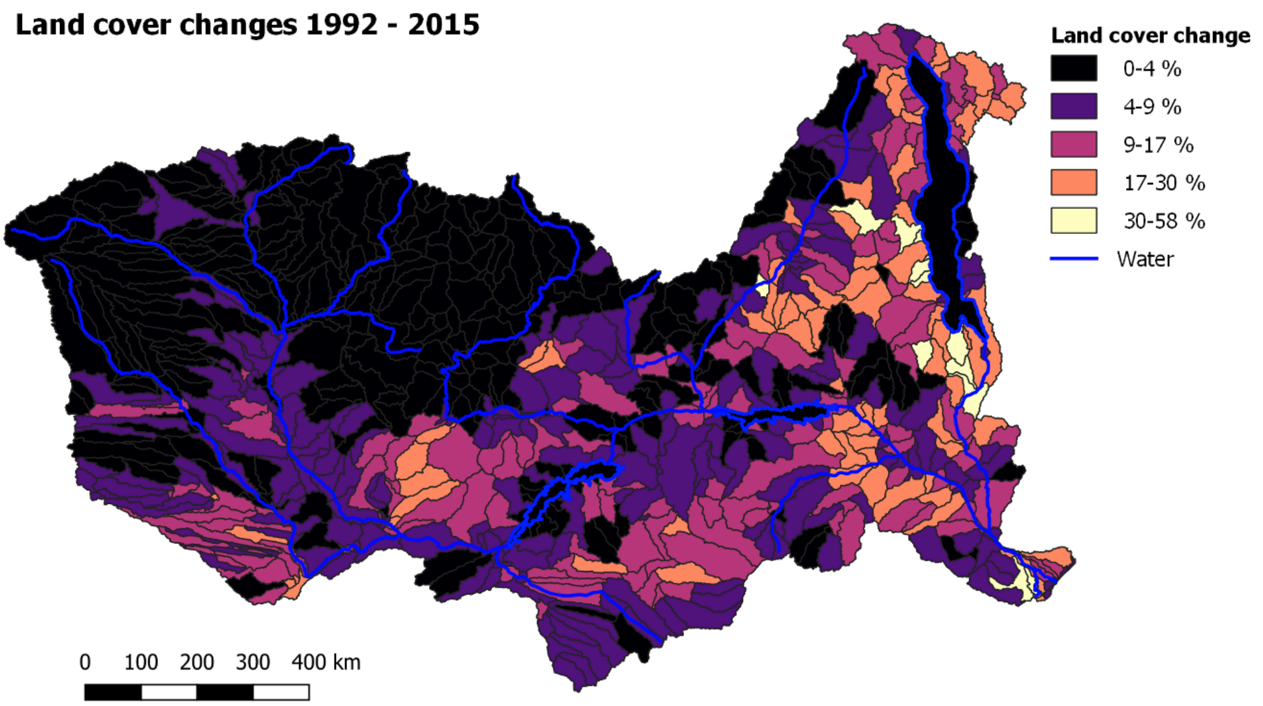


Figure 17 – Percentage of watershed surface that underwent a change in land use or land cover from 1992 to 2015 in the Zambezi (A) and Omo-Turkana basins (B). For the exact transitions of land-cover classes see Table 7 (Based on ESA CCI Landcover time series).

Table 7 – Transition matrix of land cover changes in the Zambezi basin in percent from 1992 to 2015 (Based on ESA CCI Landcover time series)

Change (%)		To									
		crop	forest	shrub	grass	sparse	wet	urban	bare	water	**Total change**
From	crop	94.85	4.84	0.23	0.01	0	0.03	0.05	0	0.01	**12.06**
	forest	3.63	93	2.41	0.41	0	0.44	0.08	0.01	0.02	**-3.17**
	shrub	1.18	5.51	93.06	0.14	0	0	0.07	0	0.03	**-1.13**
	grass	1.14	1.75	0.06	96.95	0	0.01	0.06	0	0.03	**2.04**
	sparse	0	0.34	0	0	99.66	0	0	0	0	**1.45**
	wet	0.12	2.13	0.01	0.02	0	96.87	0.01	0	0.85	**7.75**
	urban	0	0	0	0	0	0	100	0	0	**106.22**
	bare	0.69	1.28	0.03	0	0	0.03	0.8	97.15	0.02	**5.91**
	water	0.25	0.21	0.26	0.11	0	0.23	0.01	0	98.92	**0.06**

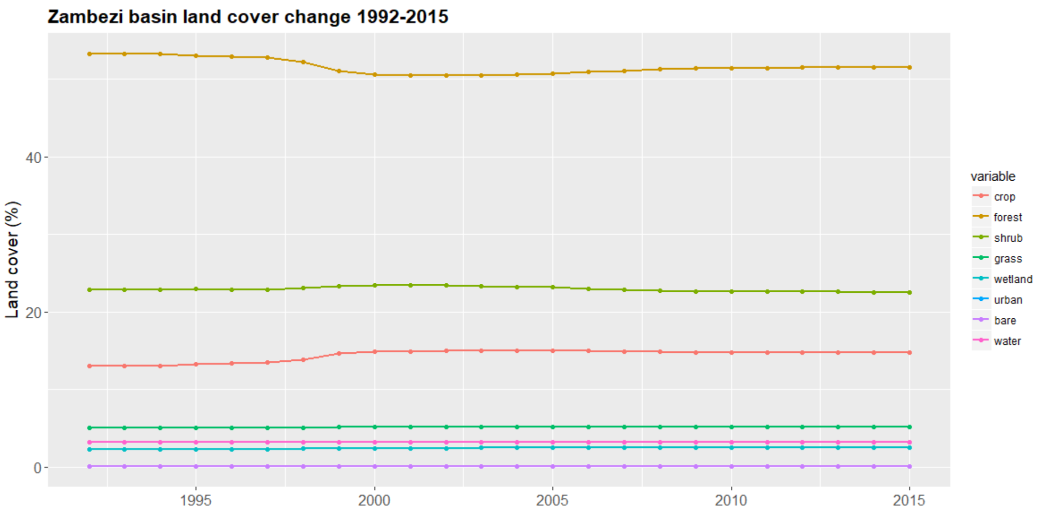


Figure 18 – Proportion of land cover classes in yearly intervals across the Zambezi basin (Based on ESA CCI Landcover time series)

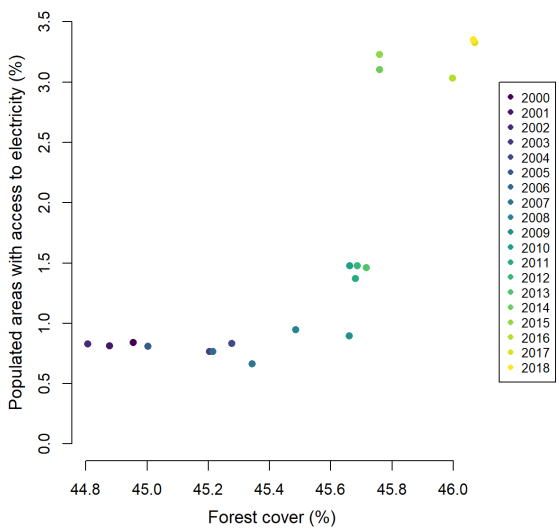


Figure 19 - Basinwide share of forest cover (based on ESA CCI land cover data) related to the share of populated areas with access to electricity over time in the ZRB. Night lights from 2000 to 2013 are based on OLS DMSP and from 2014 to 2018 on the VIIRS sensor, explaining the jump between these intervals.

Riparian vegetation in arid regions shows strong distinctions depending on overall water availability and seasonal fluctuations of floods. Changed flow regimes resulting from dam building and water abstraction can change overall vegetation dynamics and lead to a deterioration in ecosystem services provided in the riparian zone. In addition, water coming out of the dam will have reduced amounts of sediment, leading to reduced deposition of soil and nutrients and increased erosion rates within the river channel due to “hungry waters”. The so-called “clear water effect”. There is an equilibrium between the kinetic energy of a stream and the sediment load. When sediments have been deposited in a reservoir, downstream rivers tend to be more erosive. [Kondolf, 1997].

Changes in flooding extent and timing have been shown to cause changes in riparian forest composition. Elevated surfaces inside the floodplain are flooded less frequently, over shorter periods, and to lesser depths than low-lying riverbanks. [Stave et al., 2005]. Encroachment of shrub and invasive herbs into grasslands can be another consequence of changed hydrological regimes. This has been reported for the Kafue flats in combination with invasions of *Mimosa pigra* [Blaser, 2013; Blaser et al., 2014].

2.4.5 Hydrologic Alteration

The index of hydrological alteration is based on 32 parameters that are grouped in magnitude, timing, frequency, duration and rate of change in water conditions [Richter et al., 1996]. Each of these parameters influences ecosystems and therefore their functioning and services. As a next step, we will correlate this index with changes in riparian vegetation. Previously, the IHA has been successfully used to explain changes in riparian vegetation in response to land use and flow regulation based on vegetation inventories [Aguiar et al., 2018] as well as historical aerial imagery [Aguiar et al., 2016].

We used the Indicators of Hydrologic Alteration Software IHA v7 [TheNatureConservancy, 2009] to generate an index of hydrologic alteration for the Kafue gorge dam as one exemplary location. This allowed us to group the hydrograph into environmental flow components (

Figure 20) that can be associated with certain ecosystem influences. The comparison of the hydrologic parameters from the list of IHA showed that in terms of maximum annual flows, the hydrograph could be grouped into three distinct phases (Figure 21):

- 1972-1981: Before and during the first years of operation of the upstream Itezhi-Tezhi dam. This may be close to natural flow patterns, as incoming flows were not regulated yet.
- 1982-2005: Water flows were mostly regulated to optimize hydropower production, even in times of drought.
- 2006-2017: At least for a few years, environmental flow releases were carried out in a more substantial way than before, due to the initiative of WWF [WWF, 2017]

These flow phases are associated with the mass-coverage of invasive floating vegetation. It seems that a large flood release of > 1100 m^3/s was needed to flush these plants out of the reservoir.

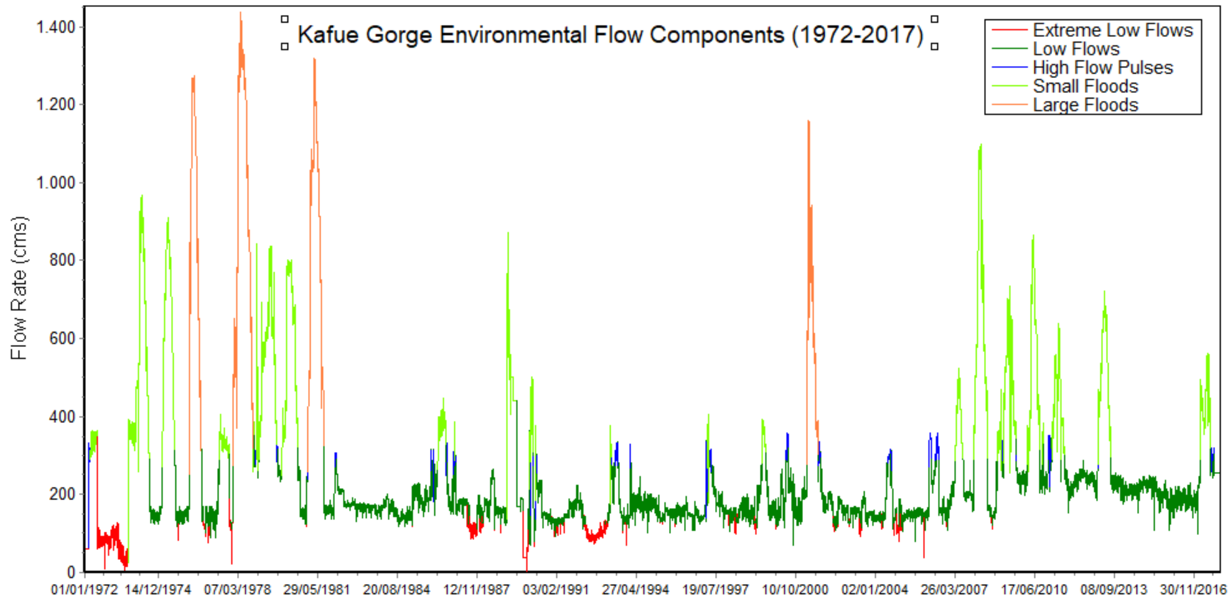


Figure 20 – environmental flow components of the Kafue gorge dam hydrograph, calculated with the software IHAv7 [TheNatureConservancy, 2009] based on data from ZESCO.

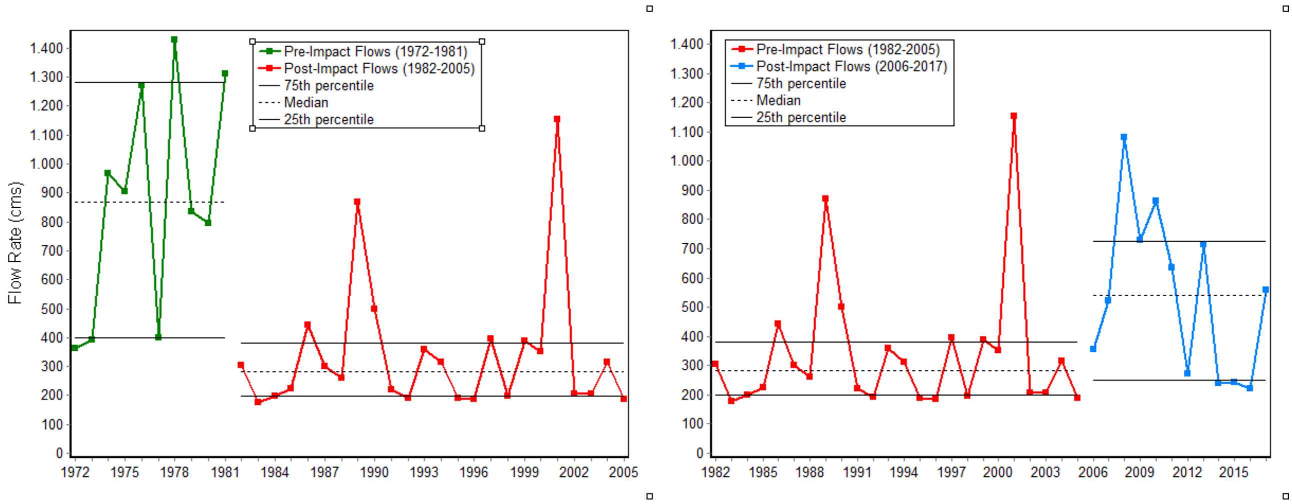


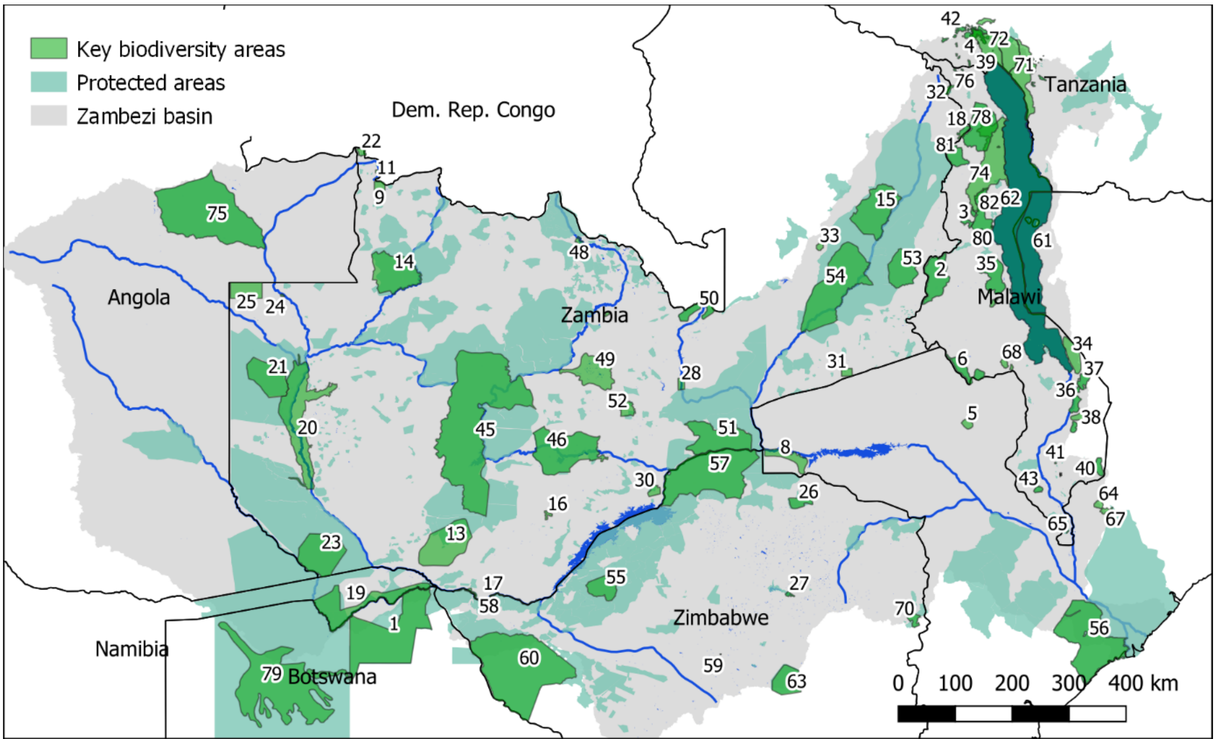
Figure 21 – The hydrologic parameter “3-day maximum annual flows” for the Kafue Gorge dam grouped into three distinct phases (1972-1981, 1982-2005, 2006-2017) separated by management interventions or impacts.

2.4.6 Tourism

The Unesco world heritage list may be the collection of the most important cultural and natural monuments in the world, all with corresponding touristic value. For the most famous touristic site in the Zambezi basin UNESCO has issued a warning as the Victoria Falls World heritage site could be affected by the impoundment behind the planned Batoka gorge dam (http://whc.unesco.org/en/decisions/7025). The Batoka gorge is also of specific importance for “whitewater rafting” as it is known as one of the best sites in the world to do this activity. Impoundment of the gorge will lead to loss of all the fast current and rapids, meaning losses for an entire part of the tourism industry in Livingstone [ERM, 2015].

2.4.7 Biodiversity

Ecosystems in teh ZRB are extremely biodiverse. Species richness has a direct value for tourism but it also enhances the resilience of ecosystems and the services they provide. Biodiversity is therefore an important indicator for the health of a system. Key biodiversity areas (Figure 22) are often the last resorts of ecosystem functioning and can act as buffers against negative feedback from landscape degradation. These KBA's should therefore be considered no-go areas for any large-scale infrastructure development that could affect their integrity. To get an idea of the distribution and compare different regions with each other, we overlaid the potential ranges of fish, bird, mammal and amphibian species and counted how many species of each group have their potential range within the same watershed (Figure 23). The results highlight the importance of the large rift valley lakes Turkana and Malawi for species conservation.



Key Biodiversity areas

1 Chobe National Park
2 Kasungu National Park
3 Mtangatanga and Perekezi Forest Res.
4 Mount Rungwe
5 Furancungo woodlands
6 Dzalanyama Forest Reserve
7 Hillwood
8 Headwaters of the Cahora Bassa Dam
9 Chitunta Plain
10 Umalila Mountains
11 Source of the Zambezi
12 Kitulo plateau
13 Machile
14 West Lunga NP and Lukwakwa GMA
15 North Luangwa National Park
16 Nkanga River Conservation Area
17 Mosi-Oa-Tunya National Park
18 Nyika National Park (Zambia)
19 Eastern Caprivi wetlands
20 Barotse Floodplains
21 Liuwa Plain National Park
22 Jimbe Drainage
23 Sioma Ngwezi National Park
24 Mbulo Forest
25 Minyanya Plain
26 Mavuradonha Mountains
27 Robert McIlwaine Recreational Park
28 Wonder Gorge
29 Livingstone Mountains forests
30 Mutulanganga
31 Nyanje Hills
32 Mafinga Mountains
33 Mutinondo Wilderness
34 Namizimu Forest Reserve
35 Nkhotakota Wildlife Reserve
36 Liwonde National Park
37 Mangochi Mountain Forest Reserve
38 Liwonde Hills Forest Reserve
39 Bulongwa Forest Reserve
40 Mount Mulanje Forest Reserve
41 Soche Mountain Forest Reserve
42 Mporoto Ridge Forest Reserve
43 Lengwe National Park
44 Thyolo tea estates
45 Kafue National Park
46 Kafue Flats
47 Imanda
48 Chimfunshi Wildlife Orphanage
49 Lukanga Swamp
50 North Swaka
51 Lower Zambezi National Park
52 Chisamba
53 Lukusuzi National Park
54 South Luangwa National Park
55 Chizarira National Park
56 Zambezi River Delta
57 Middle Zambezi Valley
58 Batoka Gorge
59 Sebakwe Poort
60 Hwange National Park
61 Lake Malawi catchment (Mozambique)
62 Lake Malawi catchment (Malawi)
63 Driefontein grasslands
64 Mount Chiperone
65 Malawi Hills Forest Reserve
66 Zomba Mountains
67 Mount Morrumbala
68 Dedza Forest Reserve
69 Ntchisi Mountain Forest Reserve
70 Nyanga mountains
71 Ruhuhu catchment
72 Lufirio catchment
73 Kipengere Range catchment
74 Nyika Plateau catchment
75 Cameia National Park
76 Misuku Hills Forest Reserves
77 Uzumara Forest Reserve
78 Nyika National Park (Malawi)
79 Okavango Delta
80 Lake-shore Forest Reserves
81 Vwaza Marsh Wildlife Reserve
82 South Viphya Forest Reserve

Figure 22 – Key biodiversity areas in the ZRB [BirdLife International, 2018].

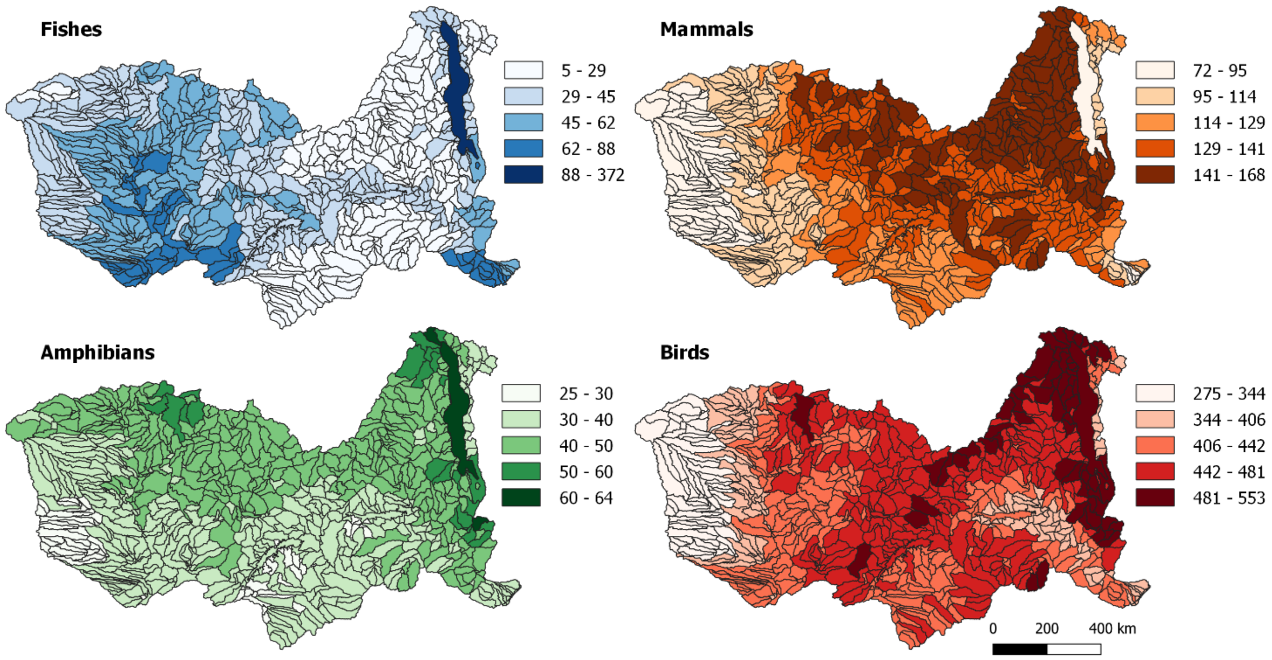


Figure 23 – Potential number of species per watershed in the ZRB, based on ranges in the IUCN Red List of Threatened Species [IUCN, 2016]

Fish

Fish are strongly affected by changes in the hydrological regime due to their feeding, migration and spawning behaviour. Four hundred and ninety species of fish belonging to 24 families have been reported in Zambia with the Barotse Floodplain having 20 species and Lake Kariba having 13 species. Habitat modification for aquatic ecosystems arises mainly from damming of rivers, siltation and introduction of exotic organisms. The damming of rivers for hydroelectric power stations has significantly affected/changed the fish fauna composition of the Middle Zambezi Basin. This regulation favours lacustrine fish species over riverine species. This has occurred at Lake Kariba where the lacustrine *Oreochomis macrochir*, has replaced most of the riverine *cyprids* and *characids* [Harding, 1964]. In the Kafue flats, impoundment has led to an increase in native Tilapia populations [Dudley, 1974] but not other fish species [Dudley and Scully, 1980].

Other species

Birds and large herbivores are important as ecosystem engineers (e.g. by dispersing seeds and nutrients) and are attractive for tourists. Environmental flow measures in the Kafue flats can be associated with positive effects on populations of the Wattled crane (*Grus carunculatus)* but not on the Kafue Lechwe *(Kobus leche kafuensis*).

A correlation has been shown between river runoff from the Zambezi river and Shrimp abundance off the coast of Mozambique [Gammelsrød, 1991]. Apparently, a well-defined dry season is better for bigger shrimps, highlighting the need to ensure both flood peaks and low water throughout the year.

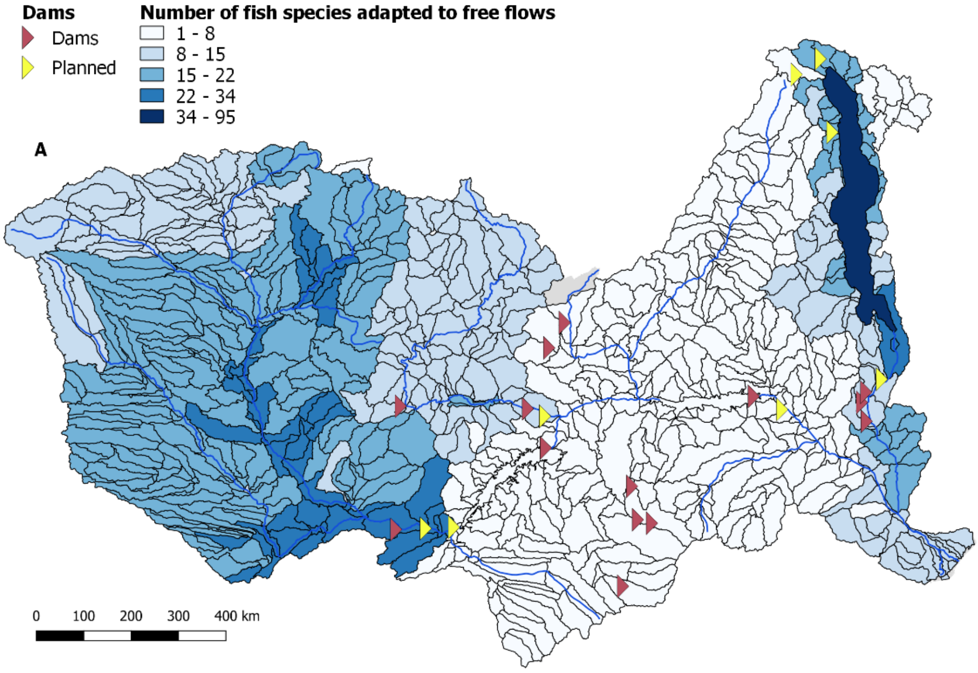


Figure 24 – Numbers of fish species with a preference for free-flowing river conditions that have their potential range in each sub-watershed of the Zambezi (A) and the Omo-Turkana (B) (Based on data from IUCN, 2016)

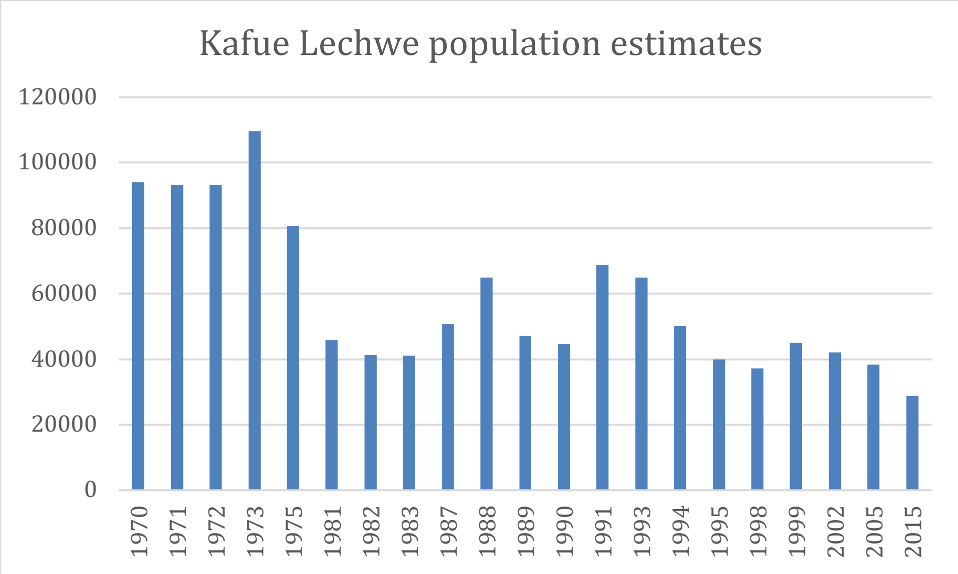
2.5 ECOSYSTEM MANAGEMENT PATHWAYS

Increasing and conflicting demands for ecosystem services make it more and more necessary to replace the self-regulating properties of ecosystems with management decisions. Such decisions are typically based on technical approaches that apply simple formulas to estimate sustainable uses of single entities (such as water). Yet, as Defries and Nagendra (2017) highlight, ecosystems are extremely complex and do not allow foreseeing all consequences of interventions across spatial, temporal and administrative scales. Therefore, Ecosystem management needs to be approached as a “wicked” problem that has not only one solution. Ecosystem management must avoid two traps: a) falsely assuming a tame solution and b) inaction from overwhelming complexity [Defries & Nagendra, 2017].With this in mind, we propose multiple pathways for ecosystem management, based on the indicators for ecosystem services outlined so far that need to be adapted to the local conditions and demands of stakeholders.

Four general pathways can be compared in the context of river management:

1) No dams and diversions
2) Expansion of impounding by construction of new dams and diversions without environmental measures
3) Expansion of impounding by construction of new dams and diversions (all or in different sets) with controlled environmental flows
4) River restoration through dam removal

The first pathway corresponds to the baseline scenario that includes all the up-to-date historic development described above. Since the second pathway does not include any environmental management, we focus here on options for the third pathway, the management of environmental flows. All these pathways will be additionally considered for scenarios of future climate as described in DAFNE deliverable D2.2. For the terrestrial ecosystems forest management and transboundary conservation will be considered as measures to define further relevant pathways.



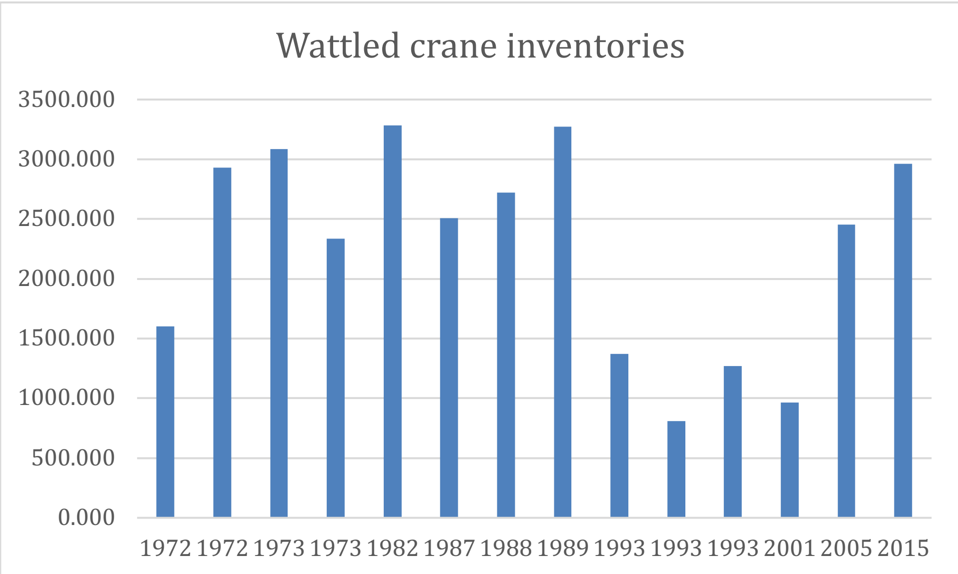


Figure 25 - Population estimates based on aerial surveys of the Kafue Lechwe *(Kobus leche kafuensis*) and the Wattled crane (*Grus carunculatus)* [Shanungu et al., 2015].

2.5.1 Reservoir Release Strategies (Environmental Flows)

Traditionally, environmental flow requirements have been imposed on dam operations in the form of release of a minimum flow. Yet, this typically does not account for varying flow regimes with flood pulses in order to provide best natural-like conditions for aquatic ecosystems. Demand curves for environmental goods and services are needed for a reservoir optimization model [Tilmant et al., 2010].

One of the few examples for environmental flow releases in the two studied basins are the Kafue flats. Itezhi-Tezhi dam was built 15% larger than intended to enable a flood flow release. When this was done in the 1970s, this was very progressive [M. McCartney, pers. comm.]. Yet, while annual releases were initially quite sporadic, significant amounts of water have only been released between 2007 and 2013 [WWF, 2017]. The effectiveness of these floodings is reflected in a strong increase in surface water dynamics during this time (Figure 26). More recent hydrographs, however, show that these flood releases have again been substantially reduced since the installation of a new hydropower plant at the Itezhi-Tezhi dam in 2015. While some potentially positive effects on wildlife (see Figure 25) may have been achieved through the flood releases, a longer time period will be necessary to monitor the ecosystem responses to these measures.

High flow scenarios

Ideally, release strategies should mimic the seasonal and yearly variation of actual inflow depending on the rainfall situation in the catchment. Our analyses in section 2.4.5 indicate that environmental flow releases may not be sufficient to achieve the desired ecosystem services outcomes (in this case the removal of invasive species), if they simply follow the same annual pattern, oriented at long-term means. A comparison of the dammed Kafue gorge reservoir with the small Maramba river in the Livingstone area shows a pronounced “trapping/growth” phase of floating vegetation, followed by a “flushing” phase (Figure 27).

Low-flow scenarios

While flow-management strategies are commonly centered around minimum flow requirements and flood releases, it is often overlooked that river catchments in strong seasonal climates also have periods of low-flow. These are important phases for example for people to use temporarily inundated areas, without getting their feet wet.

Yet, year-round hydropower production leads to constant releases of the same amounts of water through the turbines, resulting in highly unnatural discharge patterns. The only solution to this is to reduce or completely stop production of electricity in periods of drought. Fortunately, these typically coincide with seasons of high wind and sun radiation. Ideally, dam projects should therefore be accompanied with the installation of wind turbines and solar-power plants to buffer periods of low flow.

2.5.2 Dam Removal

As dams grow older, it will be important to re-evaluate the profitability of hydropower generation, given higher maintenance costs due to ageing of the infrastructure and different energy market structures (e.g. due to the expansion of production exploiting solar radiation). On the longer term, the removal of inefficient dams will make sense from an ecological and economic point of view, as increasing maintenance costs can be saved.

Examples from northern countries for dam removal as a means of river restoration are promising [Van Looy et al., 2014] but need to be adapted to the individual types and conditions of dams [Poff and Hart, 2002]. Generally, the feasibility of dam removals decreases with their size. One of the few examples for successful dam-removal in African was the Kanniedood dam located in South Africa’s Krüger National Park that was taken down in April 2018 (http://wwf.panda.org/wwf_news/?326440/Dam-removals-gather-pace-but-new-hydropower-projects-threaten-migratory-fish-across-the-world). In the ZRB, limits in water availability and low quality may soon require the removal of some of the irrigation dams that have been built in an unplanned way e.g. in the Lunsemfwa catchment (Figure 28). It may still be too early for other, more substantial dam removals, but it is obvious that dams will not last forever and ideally already at the time of project design, a removal strategy needs to be implemented.

2.5.3 Forest and Land Cover Management

To control erosion and catchment areas, but also to maintain livelihoods and biodiversity, measures are necessary to limit unsustainable forest uses and clearing for agriculture. Forest management includes regulation but at the same time valuation of logging and the use of non-timber-forest products as an alternative to clearing for agricultural uses. The distributed DAFNE model can identify the areas that are more prone to surface diffused erosion. Given the trends shown in chapters 2.4.4, measures to reduce deforestation and forest degradation are especially necessary in those areas of the Zambezi basin with high densities of **rural** populations. Forest degradation is closely linked with the use of firewood and charcoal production. This is in part because electricity is either not available or the prices are too high in most African countries. Forest use is therefore part of the WEF nexus in that different sources of energy are directly or indirectly linked to each other.

2.5.4 Trans Frontier Conservation

In contrast, the idea of Peace Parks or Transboundary Conservation Areas has been pioneered in Southern Africa and provides a positive example, how conservation across borders can be shaped by integrative measures [Ali, 2007]. Building an identity for an entire region or watershed can attract tourists but also provide incentives to decision makers and local populations to engage in constructive solutions to complex conservation issues. A positive example for a popular trans-frontier conservation area is the Zambezi-Kavango system in the bordering region of Zambia, Zimbabwe, Botswana, Namibia and Angola [Busch, 2008; Suich et al., 2005]. Another example is the ZIMOZA park in the bordering region of Zimbabwe, Mozambique and Zambia that was established in 2010 supported by World Bank and the German GIZ.

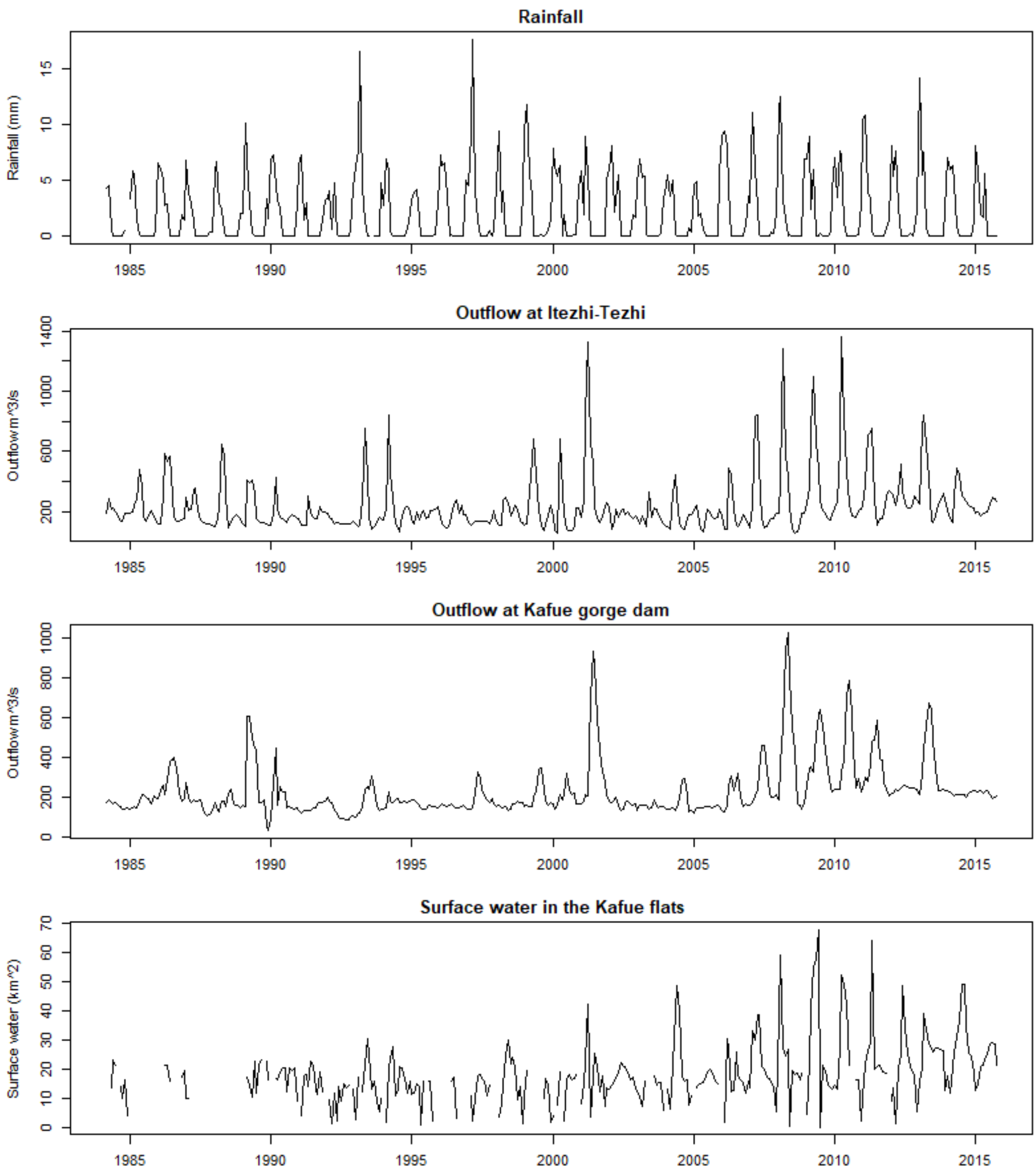


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Figure 26 - Rainfall, discharge at Itezhi-Tezhi and Kafue gorge dams (source ZESCO) combined with surface water data based on Landsat images [Pekel et al., 2016]. Improved dam operation rules at Itezhi-Tezhi have been operational since 2007 [WWF, 2017].

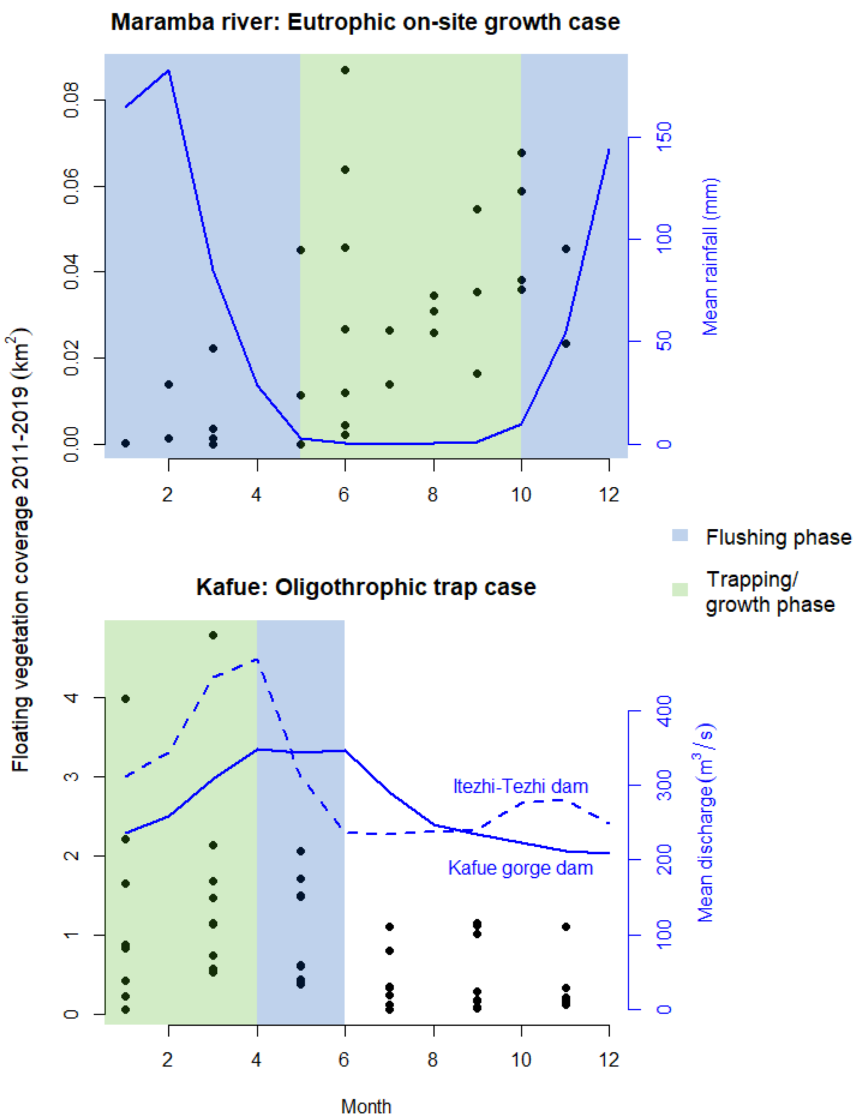

Figure 27 – Seasonal cycle of invasive floating vegetation in conjunction with hydrology between 2011 and 2019 (Winton & Kleinschroth in prep.). Black dots denote observations of floating vegetation cover (based on Google Earth for Maramba, Landsat for Kafue). Blue lines and axes show rainfall (catchment wide extract from CHIRPS dataset [Funk et al., 2014]) and discharge (ZESCO data).

Figure 28 – Broken irrigation dam in the Lunsemfwa catchment in Zambia (picture by Fritz Kleinschroth)

3. OMO-TURKANA BASIN

3.1 OVERVIEW OF ECOSYSTEMS

The Omo River and Lake Turkana form a unique geographical constellation: water from the Ethiopian highlands flows to the arid lands of the rift valley, where it forms the world's largest desert lake. This constellation combines a diverse range of ecosystems including mountain forests and wetlands, riparian forests and a delta that terminates in a terminal lake, all of which support highly specialized livelihoods. People in the Omo-Turkana basin depend directly on ecosystem services generated within the landscapes they inhabit. At the same time, people across Ethiopia and Kenya, depend on the water resources originating in the forests of the upper parts of the basin.

Yet, major changes are underway. Drivers of change in the river systems such as construction of dams and large-scale irrigation schemes, combined with climate change, threaten natural patterns and fluctuations of water availability. Here, we analyze where and how people have been affected (positively and negatively) by changes in ecosystem services and outline potential mitigation strategies.

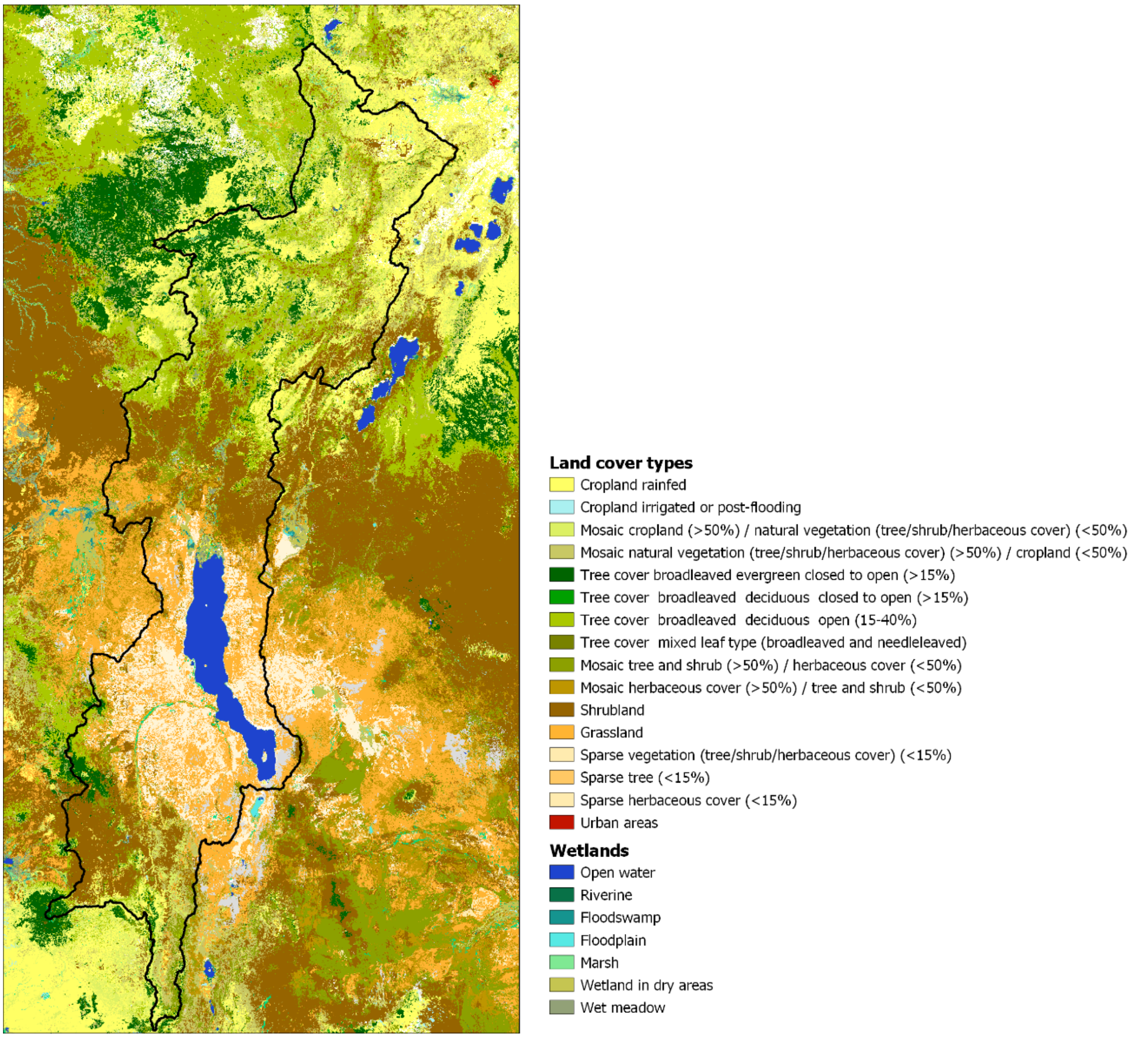

Figure 29 – Land cover classification for the Omo Turkana basin (Terrestrial: ESA CCI land cover map, Wetlands: [Gumbricht, 2012])

The Omo Turkana Basin can be divided in the upper northern part dominated by forests and agriculture and the arid southern part around Lake Turkana that is mostly desert and shrubland with some seasonal grasslands (Figure 29). The total population of the basin is estimated to be approximately 15 million, the vast majority of whom live in the northern part of the basin, in the Ethiopian highlands.

The water of the Omo River mainly originates in the Ethiopian highlands. While the north-western edge of the catchment towards Addis Ababa is characterized by croplands and few remaining forests, the north-western part is still widely under forest cover. Three tributaries of the Omo have their sources in the Kafa region: The Gojeb river drains into the Omo inside the newly created Gibe III reservoir, while the two others join the Omo just above the Kuraz sugar plantations and the Omo national park. Streams in the upper catchment are characterized by a steep topography and highly diverse habitats, featuring waterfalls, gorges, wetlands and old growth forests. All these features contribute to the habitat diversity of the Eastern Afromontane biodiversity hotspot.

The lowlands of the Omo catchment are characterized by low rainfall and only the main stem of the Omo River is perennial. Here, the river is characterized by slow-flowing, turbid waters, forming regular meanders. The permanent water availability allows the growth of riparian vegetation (Figure 30). The relatively sharp boundaries between the closed canopy woodland along the river and the more xerophytic surrounding vegetation is maintained by regular fires [Carr, 1998].

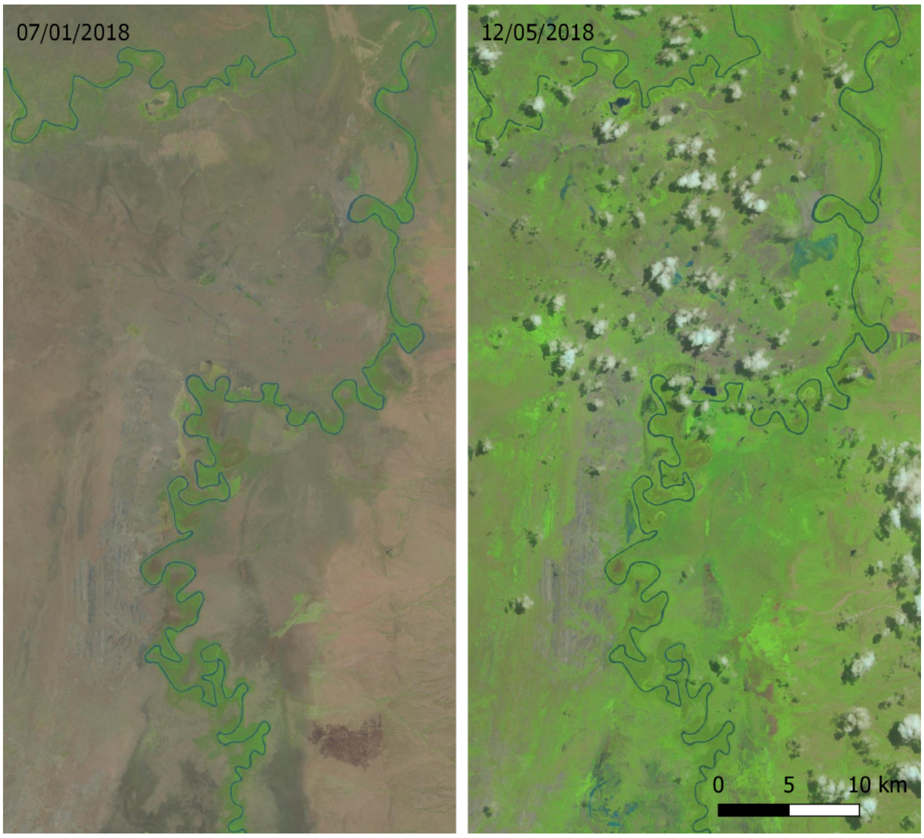

Figure 30 – The course of the lower Omo river before it drains into Lake Turkana as seen on Sentinel 2 images during contrasting seasons (courtesy of the Copernicus programme).

3.1.1 Lake Turkana

Lake Turkana is the world's largest permanent desert lake, providing water resources and extremely valuable habitats in an otherwise arid region. Located in the East African Rift Valley, the area around the lake is of high importance for archaeological traces of the "cradle of mankind" [Ojwang et al., 2017]. Due to its remote location, Lake Turkana has been the last of the Great Lakes of Africa to be studied in detail. High levels of salinity and alkalinity provide an extreme environment that nevertheless hosts high densities of fish [Hopson, 1982]. The fish fauna of Lake Turkana is derived from the Nile system and comprises 48 species with 11 endemics, which is a relatively low proportion in comparison with other African lakes [Muška et al., 2012]. Most fisheries take place in the littoral areas with water up to 10 m deep (Figure 31) [Hopson, 1982].

While macrophytic vegetation is relatively sparse, it has an important role in providing fish with food and shelter from predators and wave action; apart from being used as a spawning habitat [Hopson, 1982]. At the same time, grassy areas along the shore are important for livestock grazing. Due to the scarcity of productive vegetation in and around the lake, direct competition between grazing animals and the fish species *Oreochromis niloticus* has been observed in the highly productive area of Ferguson's gulf [Hopson, 1982]. At the same time, livestock also fertilize the soil and may contribute to nutrient inputs to the water, which potentially benefits the fish.

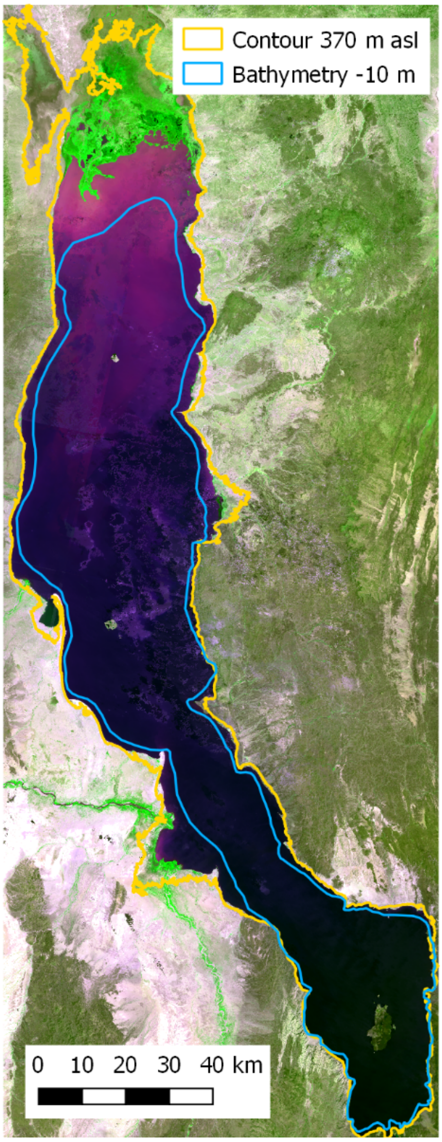

Figure 31 – Lake Turkana as seen on a Landsat 8 OLI mosaic (January 2018, courtesy of US Geological Survey), overlaid with the 370 m contour line, [Zyl, 2001], delimiting partly vegetated areas around the lake and the approximate -10 m bathymetry line, indicating the extent of most fishery activities [Hopson, 1982].

3.1.2 Wetlands

The major wetlands in the basin include those occurring along rivers and streams such as Turkwel and Kerio (Kenyan portion of the basin); and Gojeb (in the Ethiopian portion of the basin – highlands of Ethiopia; Table 8). Palustrine wetlands which comprise marshes, swamps, bogs and floodplains also occur in the basin. This include; Alemgono and Chidi (in the highlands of Ethiopia, see Table 8) and potentially Lotikipi Swamp in Kenya, which is an endorheic basin in itself. The ecological importance of the Alemgono wetland (a wetland in the Omo-Gibe river) is internationally recognized due to its importance for migrating and endemic birds. Alemgono wetland is attractive as a breeding and feeding ground for endemic birds, such as the Wattled Crane (*Bugeranus carunculatus*) and Rouget's rail *(Rougetius rougetii*) as well as resting sites for migrating birds like Yellow wagtail (*Motacilla flava*) and Red-throated pipit (*Anthus cervinus*) [Dresen, 2015].

Human-made lakes such as reservoirs behind irrigation and hydroelectric dams include the cascades of Omo-Gibe hydroelectric dams, in Ethiopia and the Turkwel dam, in Kenya.

Table 8 - Characteristics of major wetlands in the Omo basin (Dresen, 2015, own observations)

Features	**Riverine wetlands**			**Palustrine wetlands**			
	Gojeb	*Turkwel*	*Kerio*	*Lotikipi Swamp*	*Alemgono*	*Chidi*	*Omo-delta*
Contributing basin	Omo-Gibe	Turkwel river	Kerio river	West of lake Turkana	Omo-Gibe	Omo-Gibe	Lower Omo-river
Catchment area (km^2)	1490	23900	17800		618	40.95	334
Area of wetland (km^2)	71			Max 7200	9.5	2.93	
Water sources	Gojeb river, tributary inflows and runoff	Turkwel river	Kerio river	Seasonal rivers	Groundwater and precipitation	Surface water run–off from the slopes and precipitation	Lower Omo river and tributaries (e.g., Mago river)
Mean flow (m^3/s)	0.6	19-25	5		N/A	N/A	N/A
Dominant vegetation	Melanthera scandens forbs and Cyperus latifolius - Vigna pakeri pastures		High altitude forest and riverine forest.	Grassy floodplain with reeds and papyrus; scattered Acacia and Balanites trees	Dominated by Cyperus Sp.	Dominated by Cyperus Sp.	Dominated by Potamogeton spp., and diverse emergent grasses

The Omo Delta is a highly dynamic and productive ecosystem, built up by sediments and shaped by water from the Omo river. Over time, typical "birdfoot" formation due to branching and deposition at the end of the river channel developed into alluvial fans that then were transformed into more estuarine formations if high water levels flood the lower levels of the delta area (Figure 32, Butzer, 1970). Vegetation development plays an important role in capturing sediment and stabilizing new land areas. Such organogenic shorelines are first established through a floating margin of sediment-binding, aquatic vegetation followed by stands of cattails (*Typha sp.*), sedges (*Cyperus*), tall reeds (*Phragmites sp.*) and other grasses further inshore [Butzer, 1971]. While morphological dynamics have remained constant over the last decades, a decline in wildlife and at the same time increasing human activity have been reported [Haack, 1996].

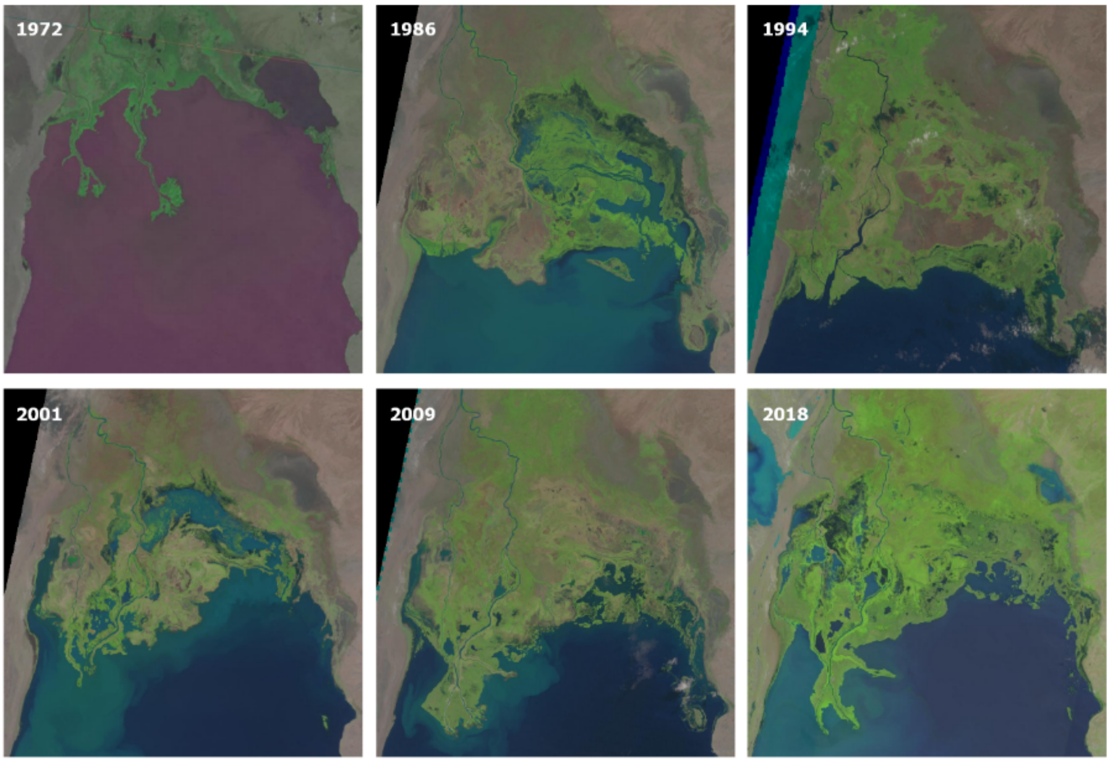

Figure 32 – Decadal dynamics of the Omo delta as seen on images captured by Landsat 1, 5, 7, and Sentinel 2 (images courtesy of US Geological survey and EU Copernicus programme)

3.1.3 Grasslands, shrublands, forests

Grasslands represent the most important grazing resources in the lower Omo extending to about 1,534 million ha [EEPCO, 2009]. They are typical in Omo National Park, the plains of lower Omo and the Mursi Bodi plains. Species like *Cenchrus Sp., Digitaria Sp., Pennisetum Sp., Elusine Sp., and Enteropogon macrostachyus* are common in the lower Omo areas. The saline area of lacustrine pasture near Lake Turkana is heavily grazed for much of the year, a disturbance in addition to the seasonal surface water logging and burning. This grassland is mainly composed of two grass species: *Sporobolus spicatus and Braciara sp*.

On its way from the uplands to the lowlands, the Omo River passes two distinct forest ecoregions. Closed canopy woodlands and forest predominate in the Ethiopian highlands. Trees in this category are represented by *Ficus sycomorus, Tapura fischeri, Melanodiscus oblongus, Celtis integrifolia* and *Trichilia roka*. The mountain forests of the Kafa region in the upper Omo catchment is known as the origin of the wild coffee plant (*Coffea arabica*) [EEPCO, 2009].

The lower Omo area is dominated by open and dense riverine woodland classes. Trees in this category are represented by *Combertum molle, Terminalia Sp., Piliostigma thonningii and Acacia Sp*. An understorey of *Harrisonia abyssinica, Dichrostachys cinerea, Grewia Sp., Acacia mellifera, Baranites aegyptica and Acacia tortolis* is also typical [Carr, 1998].

The Turkwell river in Kenya, follows a similar trajectory (although much shorter) from the slopes of Mount Elgon to the Turkana desert. Here, riparian forests with a maximum height of 20 m, extends 1-3 km on both sides of the river channel. While the canopy is dominated by *Acacia tortilis*, the understorey contains large woody herbs such as *Acalypha fruticosa, Abutilon hirtum, Abutilon fruticosum* and *Kosteletzkya begoniifolia.* In the dry season, however, the ground is mostly bare [Stave et al., 2005].

3.2 OVERVIEW OF ECOSYSTEM SERVICES

3.2.1 Provisioning services

Water provision

Rivers and wetlands are unique and essential in providing drinking water to inhabitants. Rivers and wetlands in the OTB are the major sources of freshwater for domestic supply for **urban** and **rural** inhabitants [Dresen, 2015].

Perennial rivers that intersect towns and cities, contribute to a significant share of the water consumption as shown for the Wabe subcatchment [Sahle et al., 2019]. Also Jimma town (population 207,000) depends on the Gilgel Gibe river as the source of raw water supply. The majority of **rural** communities depend on shallow hand-dug wells from alluvial deposits in plains and in strips along river courses [Ayenew and Becht, 2008]. The principal source of water supply for livestock and human consumption in the lower Omo and adjoining regions are river bed excavations and hand dug wells drilled into the river beds, and the Omo river [Kebede, 2012]. For drinking purposes the local people inhabiting the Omo river use the root of a plant locally called Gluf (*Maerua Subcordata*) and known to be rich in polysaccharides (good as coagulating agent) to physically purify the otherwise turbid Omo river, as there is very scarce modern water purification technology [Kebede, 2012].

In the Southern Nations, Nationalities and People's (SNNP) region, where 75% of the Ethiopian portion of basin is located, 43.4% of the population has access to safe drinking water, out of which 42% live in **rural** areas and 65.1% are in **urban** area [Wandera et al., 2008]. However, there is high variation among woredas (districts) located in the Ethiopian portion of the basin [Deneke and Hawassa, 2008].In the Kenyan portion of the OTB, mainly in the Turkana county, there is only one Water Company – LOWASCO [USAID, 2016]. The main water sources in the county comprise protected springs, protected wells, boreholes, piped water into dwellings, collected piped and rain water; while unimproved sources include ponds, dams, lake, stream/river, and unprotected springs wells. In Turkana county, only 28% of the households (23,000 out of 80,921 households) have access to potable water, and the average distance to the nearest potable water point is 10 km [USAID, 2016].

Fisheries

While traditionally eating fish has not been part of the livelihoods of most pastoralist tribes, fisheries in Lake Turkana has been promoted by international organizations since the 1970's [Kolding, 1989]. With population growth and increasing fluctuations in the availability of land for grazing and recession agriculture, fisheries has become a major source of nutrition and income, mainly for inhabitants of the Turkana counties, but also in the Dassanech woreda in Ethiopia (Figure 33) [Carr, 2017].

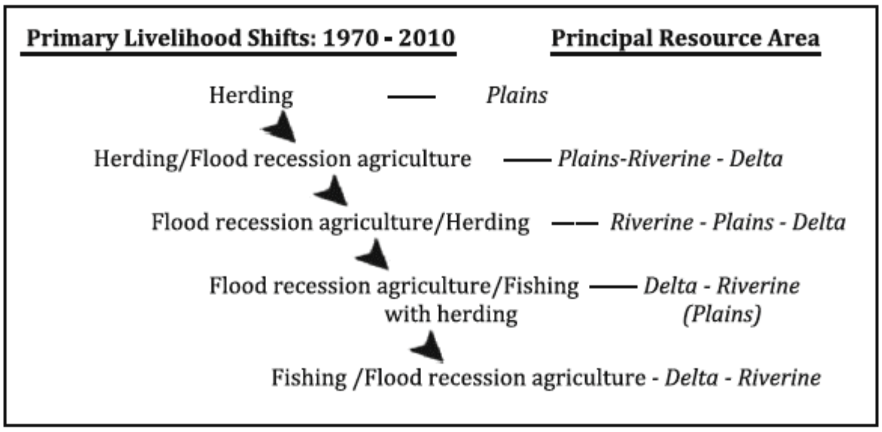

Figure 33 - Livelihood shift of the Dasanech tribe in the Lower Omo Valley from upland pastoral economy to fisheries and flood recession agriculture [Carr, 2017]

Although Lake Turkana is semi saline and unsuitable for agricultural activities, it is home to at least 60 species of fish, the world's largest remaining population of Nile crocodile and an endemic Turkana mud turtle (*Pelusios broadleyi*). Table 9 summarizes the quantity and value of capture fish production in the Turkana county in Kenya (mainly from Lake Turkana and Turkwel reservoir). The proportion of fish capture in the Turkana county in relation to the national fish capture from fresh water varied between 2.1 and 4.9%; i.e., 4.9% in 2010, 2.4 in 2011, 2.1 in 2012, 2.8 in 2013, and 2.6 in 2014.

Table 9 - Quantity and value of capture fish production in the Turkana county [Source: [Ministry of Agriculture Livestock and Fisheries, 2015]]

	2010		**2011**		**2012**		**2013**		**2014**	
	Qt. (MT)	Value (US$)	Qt. (MT)	Value (US$)	Qt. (MT)	Value (US$)	Qt. (MT)	Value (US$)	Qt. (MT)	Value (US$)
L. Turkana	6430	3,383,400	3746	3,242,672	3001	3,658,874	4338	5,005,089	4165	4,790,602

Flood recession agriculture

Flood recession agriculture may be one of the oldest ways of farming. Wealth and growth of Ancient Egypt would not have been possible without the annual flooding of the Nile River that brought water and nutrient-rich sediment in an otherwise arid region. The years when the river "failed" to flood the plains have been associated with revolts and interstate conflict [Manning et al., 2017]. In the OTB, flood recession agriculture is still a common practice and of high importance for **rural** communities without access to markets and products from industrialized agriculture.

In Ethiopia and Kenya, recession agriculture is an important part of flood-based farming. Floods are important to replenish soil nutrients, recharge soil moisture, and encourage high agricultural activity [Ayalew, 2009]. In the Ethiopian portion of the OTB, flood recession agriculture is carried out in the Omo delta and in narrow bands along the banks of the lower Omo Valley (Figure 34). Flood recession cropping is important in all four Woredas of the Ethiopian portion of the basin: Hamer, Salamago, Nyangatom, and Dassanech. The estimated number of population engaged in flood recession agriculture in the lower Omo valley varies between 66,000 -100,000 people [Sogreah, 2010; Woodroofe, 1996], who mainly cultivate maize, sorghum and finger millet [Richter et al., 2010]. EEPCO, (2009) estimate a total area under recession agriculture of approximately 11 000 ha for the lower Omo. A more long-term account of the state of recession agriculture in the Dassanech woreda (which includes the lowest part of the Omo and the delta) shows strong fluctuations in cultivated area from year to year with by far the lowest values reported in 2017 and 2018 (Table 10). The results of a 2019 field-based account confirm this trend as shown in Figure 35. This decrease is also reflected by our own field-based observations of cropped areas in 2019, compared with satellite-based observations from 2011 (Figure 35). In the Kenyan portion of the basin, mainly in Turkana county, the potential flood-based farming (recession agriculture) is estimated at 858 ha [Yazew et al., 2015]. The link between recession agriculture and flow dynamics is explored in chapter 3.4.3.

Figure 34 – Flood recession field in the Lower Omo Valley south of Omorate (picture: F. Kleinschroth)

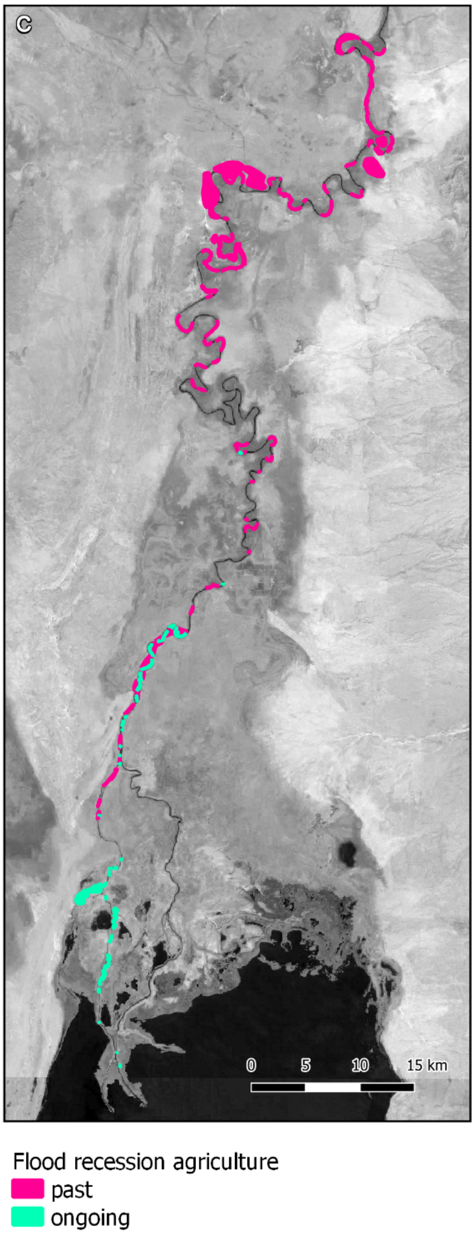

Figure 35 – Field-based account of ongoing flood-recession agriculture (March 2019, only the western branch of the river in the delta was covered) compared to abandoned areas that were detected with active cultivation on high resolution imagery (Bing maps, approximately from 2011).

Table 10 – Area (ha) of flood recession agriculture in the Dassanech woreda by year reported by different sources

Year	RapidEye remote sensing observations (F. Semeria)[1]	Data from woreda administration [Yntiso, 2012]	Data from woreda administration (unpublished)	Field observations (F. Kleinschroth)
2006	1712.8			
2007		650.7		
2008	736.1			
2009		501.0		
2010	721.2	397.3		
2011	1376.1	1052.2	1045.6	
2012	751.5		821.5	
2013	379.3		340.2	
2014	303.7			
2015				
2016				
2017			191.6	
2018			30.2	
2019				203

Livestock grazing

The livestock population, including poultry, of the Ethiopian portion of the basin is estimated at 36 million [CSA, 2017]. Cattle, sheep and goats constitute 62.4% (22.5 million) of the livestock population. Cattle alone constitute about 34% (12.2 million) of the livestock population in the basin, and constitute 20.5 % of the cattle population of Ethiopia (i.e., the total cattle population in Ethiopia is estimated at 59,486,667). The livestock population in the Kenyan portion of the basin is estimated at 11 million [Ministry of Agriculture Livestock and Fisheries, 2015]; goats cover about 54% of the livestock population whereas cattle and sheep covers 14 and 32% of the livestock population, respectively. The Cattle population in the Turkana county covers about 8.6% of the national cattle population, sheep covers about 20.2%, and goat covers about 23.6% of the national population. Most important sources of livestock feed in the basin are natural pastures/grazing lands, wetland, and crop residues [Ndathi et al., 2013]. Natural pastures/grazing lands (i.e., green fodder) contribute a greater proportion followed by crop residues [CSA, 2017]. Similarly, the majority of households in the Turkana county use green fodder as a source of livestock feed [Ndathi et al., 2013]. The crop residues are mainly obtained from rainfed and the recession agriculture in the basin. Natural pasture/grazing lands in the basin produce a great variety of ecosystem services by supporting the livestock population including milk and egg.

Own observations show that especially in the Omo delta, the most attractive grazing grounds are in the areas that are influenced by river floods (Figure 36).

[1] Digitized from RapidEye satellite imagery as part of an MSc thesis at Politecnico di Milano

Figure 36 – Temporarily flooded area in the Omo delta with recession agriculture in the foreground and grazing areas in the background (picture: F. Kleinschroth).

Table 11 - Number of livestock and annual livestock products in Omo-Turkana basin (Source: Ministry of Agriculture Livestock and Fisheries, 2015; CSA, 2017)

Livestock				**Livestock products**		
Type	*Ethiopian portion*	*Turkana county*		*Types*	*Ethiopian portion*	*Turkana county*
Cattle	12,199,769	1,534,612		Milk (kg)	629,245,920	52,601,269
Sheep	5,324,842	3,517,148		Beef (kg)		313,200
Goats	4,995,856	5,994,881		Chevon (kg)		1,073,262
Horses	478,000	-		Mutton (kg)		456,800
Mules	70,651	-		Pork (kg)		3,000
Donkeys	931,217	-		Camel milk (kg)		240,000
Camels	1,581	-		Honey (kg)	9,411,433	103,134
Poultry	10,570,631	-		Egg (kg)	19,699,209	244,080*
Beehives	1,495,567	-		Skin (No.)		264,208
				Hide (No.)		4,004

*the value is given trays

Forest products

Especially in the arid lower Omo region, shrublands and forests provide resources that are of fundamental importance to the region's pastoralist communities who use them for grazing, bushmeat hunting, beekeeping, gathering of wild plants, fruits timber, fuel and fibre (Figure 37) [Hodbod, Tebbs, et al., 2019]. Forests near the river often play a significant role in coping strategies during extended periods of drought [Carr, 2017].

3.2.2 Regulating Services

Regulating ecosystem services include climate regulation, controlling the hydrological flows of water, water purification, soil erosion control and providing a habitat for pollinators [WRI, 2005]. By regulating biophysical phases and processes, natural ecosystems make a vital contribution to occupations and economic development through the prevention and alleviation of damage that inflicts costs on society [Carpenter and Folke, 2006].

Flow and flood regulation

The major ecosystems in the basins, such as forest, woodlands and wetlands, help to slow the speed of floodwaters thereby limiting the detrimental effects of floods and controlling soil erosion [Uluocha and Okeke, 2004]. For example, a study in Gibe I dam found that siltation and nutrient enrichment were the major problems in this reservoir [Devi et al., 2008]. Thus, in the upper catchment the indirect but considerable benefit of flood/erosion control could be that of avoiding damage to water infrastructures such as hydropower and irrigation dams.

In the lower basin, while floods are beneficial for many ecosystem services (e.g. flood recession cropping and livestock grazing), they can also be highly destructive and present a danger to human lives. For example a major flood in August 2006 in the Lower Omo basin killed 364 people, inundated 14 villages, and destroyed farmlands [Ayalew, 2009].

Soil erosion control on the other hand ensures retention of fertile topsoil and in turn ensures the sustainability of agriculture, one of the larger sectors of the basin. Major ecosystems also provide a habitat for beneficial insects such as pollinators. Wetlands in the basin are, for example, an important habitat for bees which support maize crop production which is also an important source of household income [Kasina et al., 2009].

Figure 37 – Riparian forests of the Omo River near Nyangatom (picture: F. Kleinschroth).

Carbon storage

For Ethiopia, Moges et al. (2010) indicated a potential to mitigate the release of 2.76 billion tons of carbon into the atmosphere if it protects and sustainably manages its forest resources. In the SNNP region, the Sodo Community Managed Agroforestry and Forestry Project certified a total of 189 027 t CO_2 over 35 years crediting period. Woody biomass stock of the country sequesters a much higher amount of CO^2 than it emits. It sequesters about 44 times and 478 times the CO_2 released by burning biomass fuel and clearing for agriculture, respectively [Bekele et al., 2015].

A study in Wolayita zone (one of the zone in the Ethiopian portion of the basin) estimated an average carbon stock of 226 t ha^{-1} from woody plants in Humbo forest ecosystem [Chinasho, 2015]. This same study estimated the value of the sequestered carbon at US$ 6087. A study in Jimma zone [Bekele et al., 2015] indicated that biomass carbon was found significantly higher in the native forest (134.34 ± 26.94 Mg ha-1) than in the coffee based agroforestry (58.27 ± 12.30 Mg ha-1) and in the annual crop field land (0.04 ± 0.03 Mg ha-1).

3.2.3 Cultural Services

Social systems

The ecosystems in the Omo-Turkana basin provide a number of cultural services such as spiritual and inspirational, recreational, aesthetic and educational services. Social systems cover all non-material, intangible and normally non-consumptive outputs of ecosystems that affect physical and mental states of people (Figure 38).

Numerous anthropological studies are available on the intimate link between customs and traditions of local communities and the dynamic availability of water in the floodplains and the delta of the Omo [Carr, 2017; Turton, 1977, 2011]. Spiritual interactions and a long cultural heritage create a unique sense of place for inhabitants that is tied to the natural environment determined by the flow of the river Omo [Hodbod, Stevenson, et al., 2019].

Figure 38 – Community meeting in the riparian forests of the Omo River near Nyangatom (picture: F. Klein-schroth).

Tourism

The environmental potential for tourism is high, as it is endowed with a variety of wildlife, and has several national parks (e.g., Omo, Mago and Turkana national parks) [Awulachew et al., 2007]. Few visitors travel to these National Parks due to their remote location and the lack of infrastructure. Visitors to Sibiloi and Central Island Park (i.e., the components of the Turkana national parks) ranged from 1,294 in 1996 to 458 in 1998. According to the Turkana County Investment Plan (2016-2020), the county aimed to drive the number of local and international visitors to 10,000 by 2017 and increase the same to 30,000 in 2019. The investment plan also aimed at increasing the average spending per visitor from Kenyan shillings 5,000 to 20,000 (i.e., 50 to 200 US$).

The newly established Kafa Biosphere Reserve in the upper part of the Omo basin has been presented as a destination for eco-tourism. It has diverse ecosystems, ranging from wetlands to old growth mountain forests and a unique cultural heritage as the origin of the coffee plant

[Schormann, 2011]. Supported by the German NGO NABU, the Biosphere reserve is promoting sustainable tourism in order to generate incomes for local communities (http://www.kafa-biosphere.com/).

3.2.4 Supporting Services

One of the important supporting services that is associated with natural systems such as wetlands is soil formation. This primarily results from the comingling of decomposing organic material with weathering rock [Costanza et al., 1997], mineral matter and sediment. The profiles of these soils vary depending on whether these occur in the wetland itself, on the wetland fringes, in the transition zone to dryland or the dryland with the former two being more amenable to hydric soil indicators [Vepraskas et al., 1999]. Wetland vegetation also traps and retains sediments transported by runoff and in so doing, controls siltation downstream [Haycock et al., 1997]. Another vital supporting service that the basin's natural systems (e.g., forest and woodlands) provide is nutrient recycling [Aerts et al., 1999].

Sediment retention

In the Omo-Gibe watershed, sediments yields have been linked with land cover changes such as in forest loss in the upstream areas of the Gojeb sub-basin [Choto & Fetene, 2019]. Through vegetation structure and composition, ecosystems regulate the quantity of eroded sediment that ends up in the river system. The sediment retention service supports the productivity of the soil that is affected by erosion, the quality of the water and the amount of sediment trapped in reservoirs and deposited in floodplains and deltas.

3.3 CHANGING DEMAND FOR ECOSYSTEM SERVICES

The demand for ecosystem services depends on human population. The total Ethiopian population in the basin is around 14 million [CSA, 2017]. The estimated total population in the Kenyan portion of the basin varied between 1.2 [S. Avery, 2012] and 1.7 million people [UNEP, 2010]. The number of people living within 50 km of Lake Turkana is around 215,000. Most of the population is concentrated in the upper fifth of the basin in the Ethiopia highlands and at the basin's southern-most limit in Kenya [Linard et al., 2012]. Most people in the Omo-Turkana basin live in **rural** areas (e.g., 88.3 and 89% of the people in the Ethiopian and Kenyan portion of the basin are **rural**), with limited livelihoods, and are mainly dependent on subsistence agriculture, pastoralism, and fishing [Kaijage and Nyagah, 2009; Yazew et al., 2015]. In the Kenyan portion of the basin, about 70% of the people are nomadic or semi-nomadic pastoralists [UNEP, 2008], although there is an increasing emergence of sedentary Turkana people.

In this deliverable, we focus on ecosystem services of free-flowing rivers (in contrast to services by built infrastructure, such as irrigation agriculture and hydropower that are discussed in other deliverables). We suggest that demand for ecosystem services of free-flowing rivers increases with population density but the services that are valued the most switch with urbanization and industrial development as urban populations and industry are expected to have higher demand for ecosystem services of regulated rivers.

3.3.1 Rural areas

To determine rural population density as an indicator of ecosystem services demand, we used annual population density maps from the LandScan project [Rose et al., 2018] and combined it with the presence of persistent night lights from the DMSP-OLS (2000-2013) and VIIRS (2014-2018) satellites, indicating electrification and urban or industrial infrastructure [Elvidge et al., 2001]. This methodology allowed us to track shifts in population and development status in a spatially explicit way. We classified four groups: A1 - low population (< 5 people per km^2) and no night-lights; A2 - higher population and no night-lights; B1 - low population and night-lights; B2 - higher population and night-lights. We defined shifts to the B2 category as a sign of urbanization

The more remote, sparsely populated areas in the center of the basin around Lake Turkana showed only limited change. This is the area, however, where people depend to the highest degree on direct provision of ecosystem services. Rural populations depend to a higher degree than urban populations on the direct provision of ecosystem services, as they are less connected to infrastructure networks and do not have sufficient financial resources e.g. to buy food produced elsewhere. One example are indigenous people and rural communities in the lower Omo valley [Stevenson and Buffavand, 2018]. The Omo delta, as a last resort for such communities who have lost their livelihoods elsewhere, has seen an increase in population since 2000

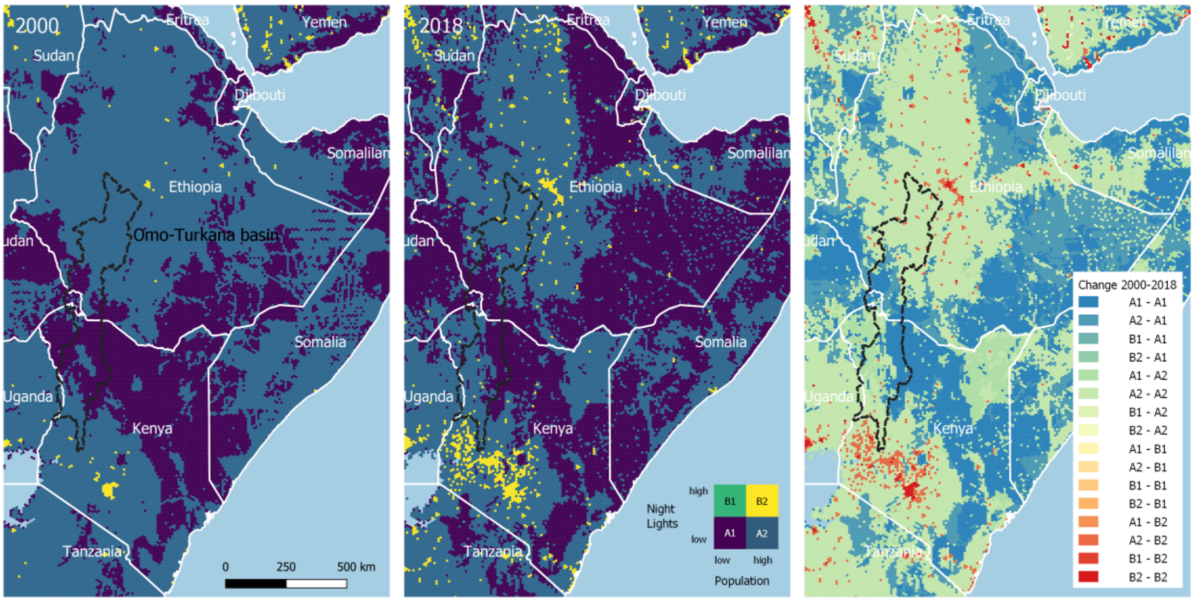

Figure 39 – Electrification, industrialization and population development in Ethiopia and Kenya from 2000 to 2018. Population density from Landscan [Rose et al., 2018], coupled with the presence of night lights from the DMSP OLS and VIIRS sensors.

3.3.2 Urban areas

From 2000 to 2018, the OTB has seen an increase in population, concentrated in the North and South due to their proximity to more urbanized regions. Especially the areas around Jimma, Sodo and Jinka have grown (Figure 40). Additionally, the OTB is adjacent to some of the fastest developing regions of the two countries with the Addis Ababa region to the north and the Kisumu area to the south. In the course of less than 20 years, these regions have multiplied their electrification as evidenced by the presence of persistent night-lights. The northern and southern parts of the basin itself also show some changes in electrification, although those are more punctual. Already for logistic reasons, the major part of produced electricity went to the cities, whereas communities living in between did not necessarily get access to the power lines that crossed their land (Figure 41). Hydropower plants may have played an important role in the production of this electricity.

The ongoing process of urbanization inside and around the OTB will change the demand for ecosystem services towards regulating functions as discussed in the case of the ZRB. This is illustrated on the remaining urban forests in the city of Addis Ababa, which provide important services, including protection from soil erosion [Woldegerima et al., 2017]. Overall, large parts of the OTB population (even in more urbanized areas) depend directly on agriculture. Here, ecosystem services such as soil and water regulating (e.g. storage and filtering) functions remain of direct importance.

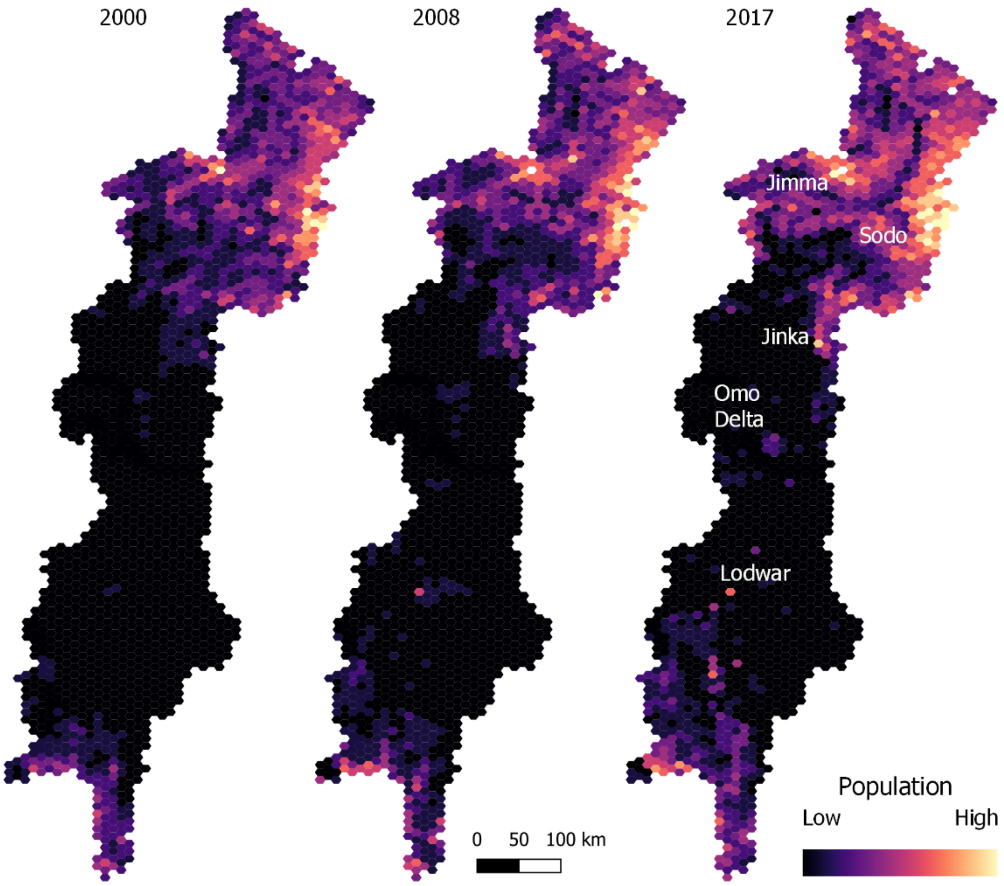

Figure 40 – Population distribution in the OTB and development over time from 2000 to 2018 [Rose et al., 2018]. Populated areas with important changes are labelled.

Figure 41 – Densely populated landscape crossed by a new power line at the northern edge of the OTB (picture: F. Kleinschroth).

3.4 CHANGING AVAILABILITY OF ECOSYSTEM SERVICES

While demand for ecosystem services has changed, also the availability did. We document processes in water and land systems of the basin that have been modified due to anthropogenic forcing such as river modifications and land use change.

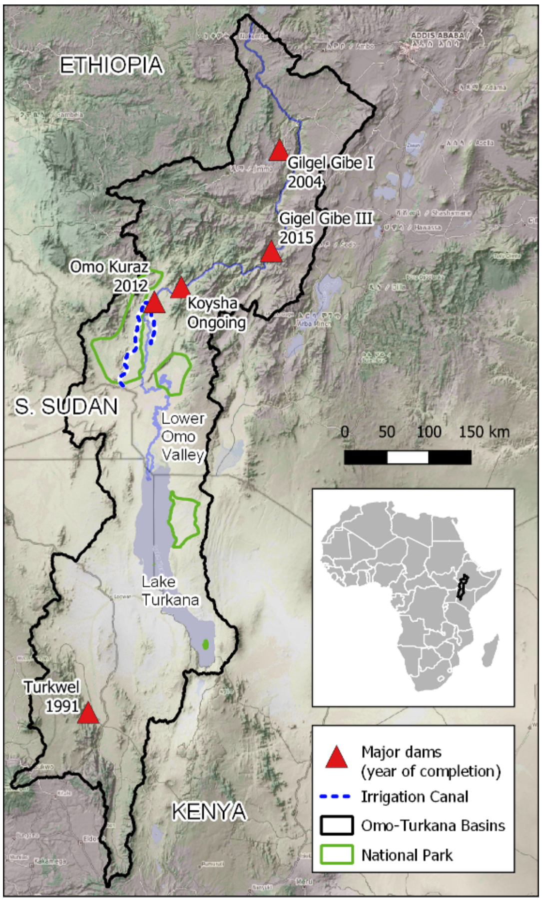

Figure 42 – Overview map of dams and irrigation projects in the OTB.

3.4.1 Forest and land cover change

Land cover, especially the proportion of cropland versus woody-plant dominated land such as forests and shrublands are important not only for provisioning ecosystem services, but also for regulating and supporting services such as carbon storage, sediment retention and water purification. We used land use change analysis based on global land cover maps from the ESA CCI (http://maps.elie.ucl.ac.be/CCI/viewer/index.php, Li et al., 2017) to show the proportion of transitions between different land cover classes from 1992 to 2015 (Table 12, Figure 43) [Moulds et al., 2015].

The highest losses appeared in the agricultural land uses (-13%), while forest strongly gained in coverage (16%). Given the fast pace of **urbanisation** (126%), this may be a sign of a forest transition, where extensive small scale agriculture is given up in favour of industrial employment in urban areas, or in intensified agriculture, which allows forest to recover on former cropland [Hosonuma et al., 2012]. At the same time, also a strong transition from bare soils to grasslands became apparent. Figure 43 shows that these changes were gradually from year to year and are therefore not due to a bias of seasonal effects in individual years. Instead, the extreme drought period throughout the 1990’s may have led to the low coverage with grassy vegetation that only recovered during higher rainfalls after 2000.

Besides climatic effects, we associate the observed land cover changes with changes in land-use and thus human behaviour. In a country-wide analysis for Ethiopia and Kenya, we plotted the share of areas with access to electricity (based on our analysis presented in section 3.3) against the share of forest cover for each year from 2000 to 2018. The relationship in both cases strongly positive. This shows that at national level, the access to electricity has an important role in reducing the pressure on forests with potentially positive outcomes for ecosystem services based on woody cover.

Table 12 – Transition matrix of land cover changes in the Omo-Turkana basin in percent from 1992 to 2015 (Based on ESA CCI Landcover time series)

Change (%)		**To**									
		crop	forest	shrub	grass	sparse	wet	urban	bare	water	**Total change**
From	crop	82.76	16.77	0.28	0.01	0	0	0.06	0	0.13	**-13.49**
	forest	0.73	99.18	0.08	0.01	0	0	0	0	0	**16.15**
	shrub	1.43	4.88	93.65	0	0	0.01	0	0.02	0.01	**-3.02**
	grass	0.38	0.18	0.01	98.79	0.19	0	0	0.39	0.06	**29.21**
	sparse	0	0	0.06	6.3	92.31	0	0	1.33	0	**88.37**
	wet	0.08	0.23	0.02	0	0	99.33	0.02	0	0.32	**1.73**
	urban	0	0	0	0	0	0	100	0	0	**126.02**
	bare	0.15	0.05	6.16	37.48	1.75	0	0	53.94	0.48	**-45.13**
	water	0.06	0	0.02	0.52	0.08	0.12	0	0.84	98.35	**-0.03**

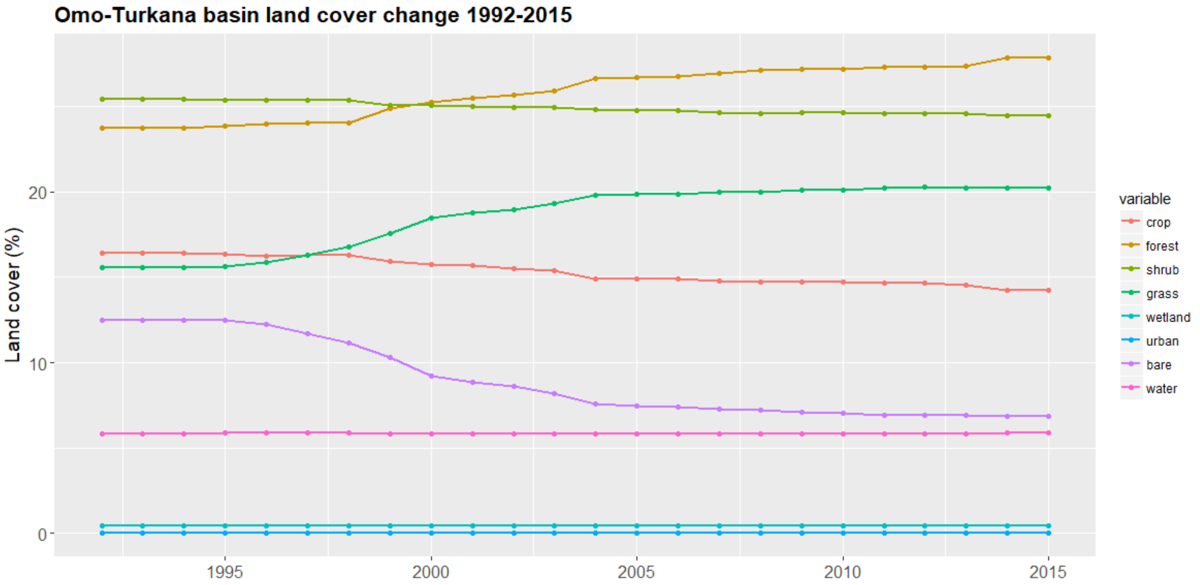

Figure 43 – Proportion of land cover classes in yearly intervals across the Omo-Turkana basin (Based on ESA CCI Landcover time series)

3.4.2 Changing flow dynamics

Dam constructions on the Turkwel and Omo rivers started in the 1990's and are still continuing in 2020 [S. T. Avery & Tebbs, 2018; Stave et al., 2005; Velpuri & Senay, 2012]. It is not well documented, when precisely those dams have been closed. We used Landsat images to determine the approximate start of reservoir filling and potential links with changes in the river system for the Gibe I, Kuraz sugar and Gibe III dams (Figure 46). Kuraz sugar dam is diverting water into an irrigation canal that is currently under construction (Figure 45) and at present 194 km long (Figure

42). Kuraz sugar dam is located ca. 250 km, Gibe III 425 km and Gibe I 560 km north of lake Turkana. According to our analysis, filling of Gibe I started in October 2002, Kuraz sugar in May 2012 and Gibe III in February 2015. These dates can serve as reference dates to detect anomalies in water availability in downstream ecosystems.

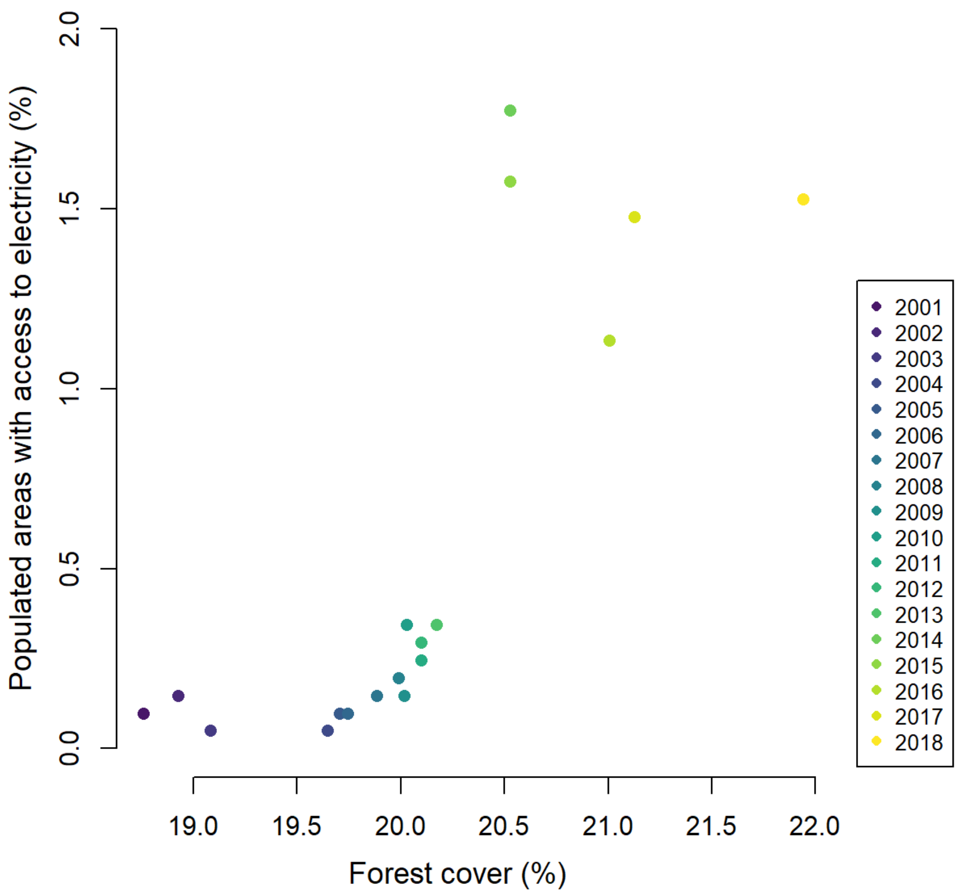

Figure 44 - Basinwide share of forest cover (based on ESA CCI land cover data) related to the share of populated areas with access to electricity over time in the OTB. Night lights from 2000 to 2013 are based on OLS DMSP and from 2014 to 2018 on the VIIRS sensor, explaining the jump between these intervals.

Figure 45 – Construction works for one of the Kuraz sugar mills, including a section of the irrigation canal to the right (picture: F. Kleinschroth).

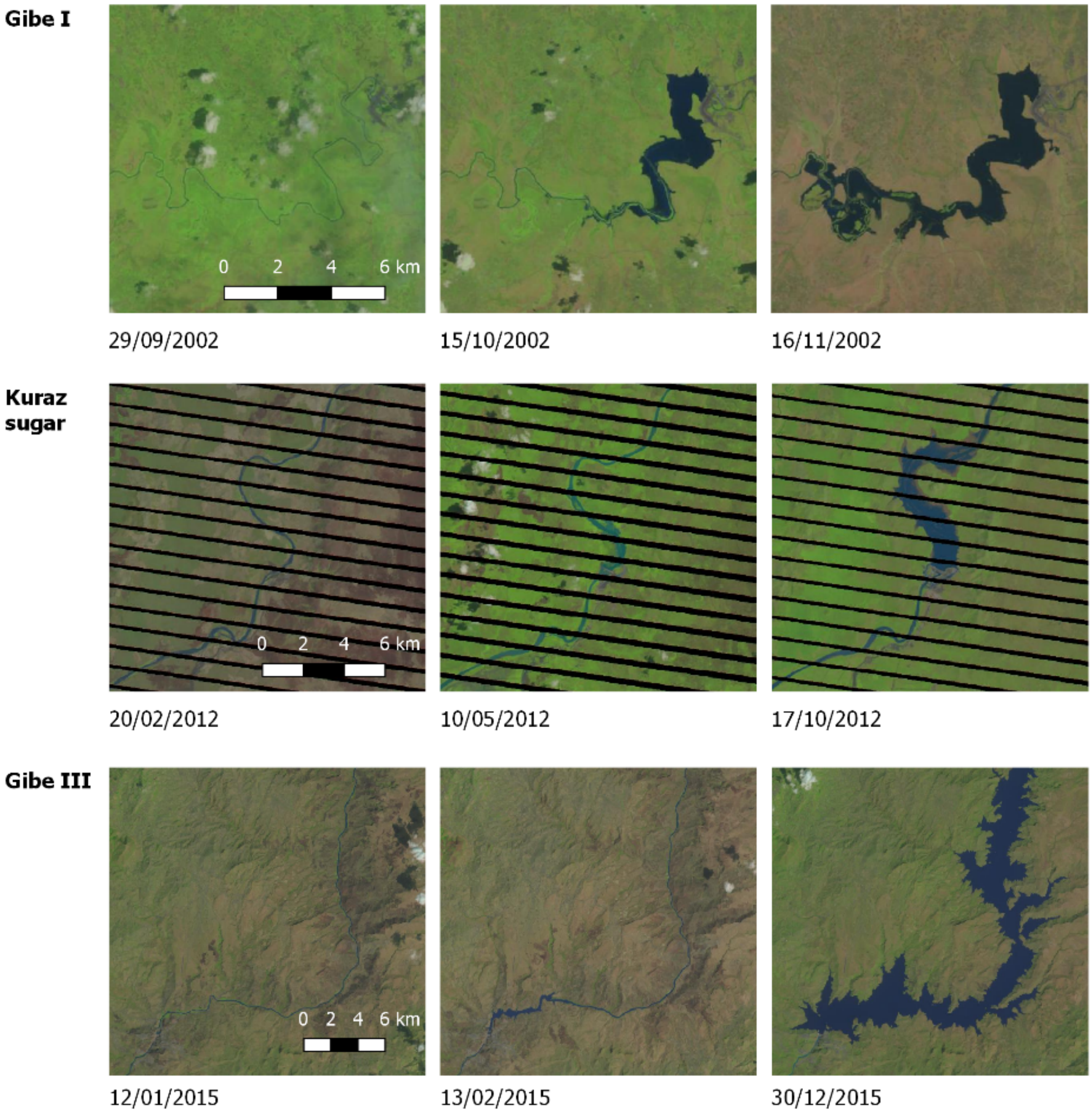

Figure 46 - Determination of the approximate start date for the filling of three dams in the Omo river catchment (location see Fig. 2). Shown are Landsat 7 and 8 images, courtesy to the US Geographical survey.

Water levels are an indicator for hydrological dynamics that can be determined remotely with relatively low biases and variations. We obtained water levels at 11 locations along the Omo river and Lake Turkana [Schwatke et al., 2015]. The estimations of river levels show differences in the magnitude of variability in water level at various locations since the construction and filling of Gibe III (Figure 46). While the levels in the newly created reservoir vary greatly, previously common seasonal oscillations in the downstream sections of the river have been reduced to almost zero at site 7. Site 10 is the only observation in the lowest part of the river and only the period from 2016 to 2019 is covered. Here, seasonal water level variations are still apparent. Levels of Lake Turkana fell during the filling period of Gibe III in 2015-2017, even more so as the filling period coincided with a climatically dry period. This effect is partially mitigated as since 2017 lake levels have risen again (Figure 47). However, the seasonal variation in flows of the Omo river have halved since 2015. This affected also the variability in Lake Turkana, where the three lowest seasonal variations since 2008 occurred after 2015. These changes have important implications for ecosystem services provided by riparian vegetation as we describe in the following sections and for fisheries as it has already been documented in the literature.

3.4.3 Flooding and surface water change

Closely linked with the precipitation regime, the levels of Lake Turkana show strong seasonal and decadal variations. Archeological studies have shown that the lake level has been in decline for about 5000 years [Bloszies et al., 2015], a trend that seems to be continued and accelerated since about 1900 (Figure 47). In the past, Turkana lake level changes have been shown to be good indicators for precipitation anomalies in East Africa [Butzer, 1970].In addition to the flow-related modifications discussed in chapter 2.4, the OTB as an endorheic basin, has the particularity that levels of Lake Turkana strongly vary with inflows from the Omo river [Gownaris et al., 2018]. Expected effects of an overall lake-level reduction due to evaporation in reservoirs and from irrigation sites are:

- Increased distance between established villages and the lake-shore with implications for food and drinking water availability
- Shallow lake areas along the shore permanently dry out leading to loss of fish spawning habitats
- Overall loss of habitat for pelagic fish species
- Increased levels of water salinity

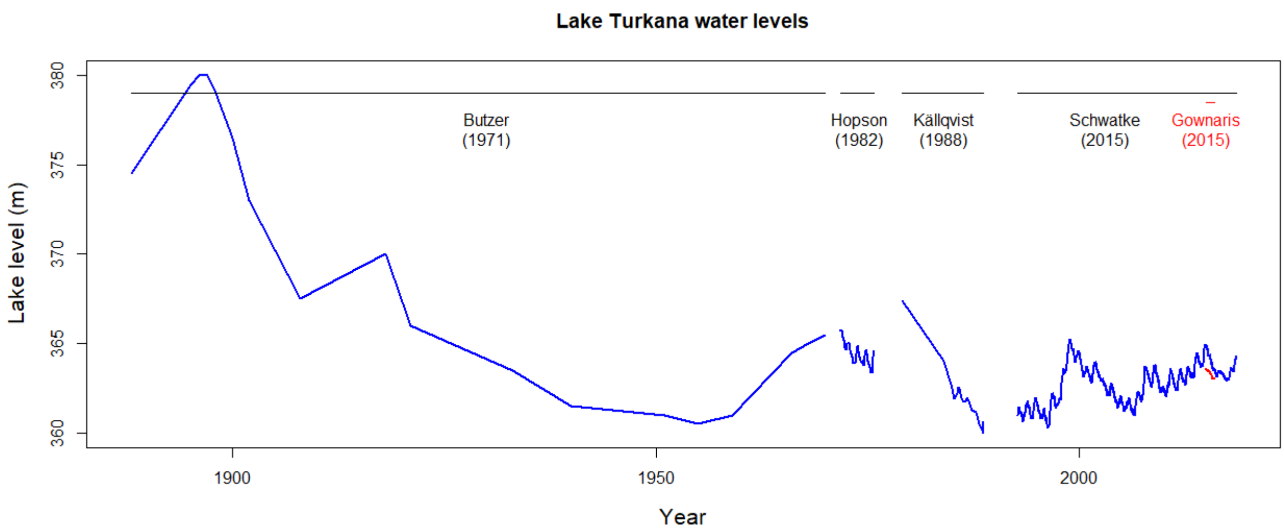

Figure 47 - Lake Turkana water levels from 1888 to 2011 [Butzer, 1971; Gownaris et al., 2017; Hopson, 1982; Källqvist, 1988; Schwatke et al., 2015]

Variations in lake levels directly affect the extent of the lake, as shallow parts of the shore get inundated or fall dry with changing water levels. These dynamics have been described as essential for fish productivity [Gownaris et al., 2017; Hopson, 1982] and pastoralism along the shore [Carr, 2017]. Important changes in lake extent have been predicted for after the closure of the Gibe III dam on the Omo river in 2015 [Velpuri and Senay, 2012]. Three years after closure of the dam, we measured the exact development of the lake extent in relation to lake levels and identified hotspots of loss and gain in lake extent.

We used a semi-automated classification approach in Google Earth Engine to determine the extent of lake Turkana from bi-monthly Landsat image mosaics between May 2013 and June 2018. Classified images (water/ no-water) were converted into shapefiles using ArcGIS. We smoothened geometries and removed all islands in QGIS. A visual comparison with the original images showed that this approach generated accurate results for large parts of the lake shore but manual correction was necessary in the north (high turbidity and shallow bathymetry) and in the south (low turbidity and steep bathymetry).

The reduction in water level during the three years since closure of the Gibe III dam have led to losses in lake surface, but less than the natural dynamics during the last three decades. Most variability was notable in the foreshore regions with shallow topography, namely the Omo delta, Allia bay, Turkwel and Kerio delta and Ferguson's gulf. False-color composite images show that these areas are also the most productive in terms of photosynthetic activity (Figure 51), thus producing important nutrients for organisms in and around the lake. In the nutrient-poor and arid region of Lake Turkana, these areas can be considered hot-spots for human food production through fish and grazing animals.

The overall levels and extent of Lake Turkana only decreased during the filling of Gibe III and showed an increasing trend since 2017. The extent of Fergusson's gulf, one of the most productive parts of Lake Turkana in terms of fish production, closely followed the trend of the overall lake levels. The lake area near the Omo delta, however, did not follow the strong decreasing trend after 2015. This can be associated with an overall retraction of the delta area that we discuss below. In both the Omo Delta and at Fergusson's Gulf we find that the seasonal variation of the shoreline has diminished since the creation of Gibe III dam following the overall patterns in river flows (Figure 49).

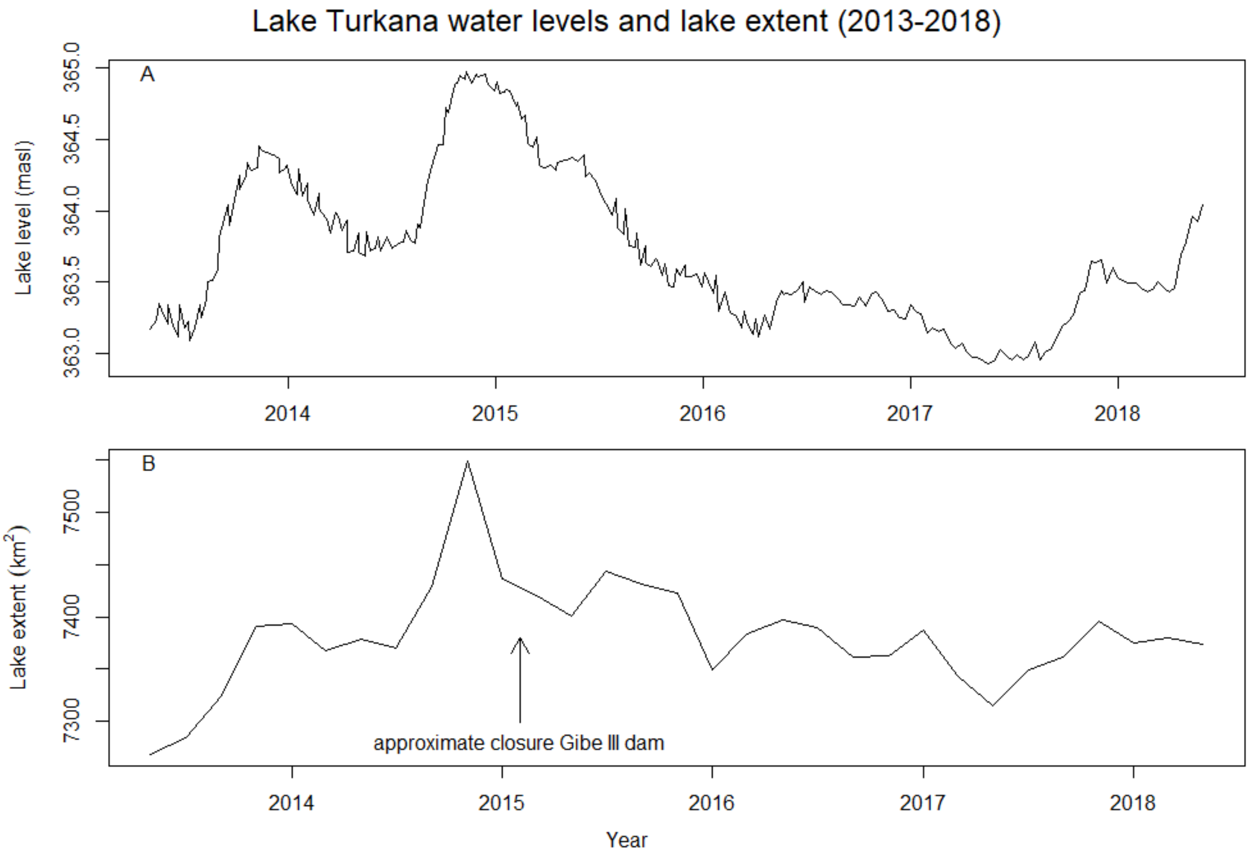

Figure 48 – A) Lake levels as measured through radar remote sensing (Crétaux et al., 2011, http://hydroweb.theia-land.fr/?lang=en&basin=LAKE%20TURKANA) between May 2013 and May 2018. B) Lake extent as observed on Landsat images during the same period.

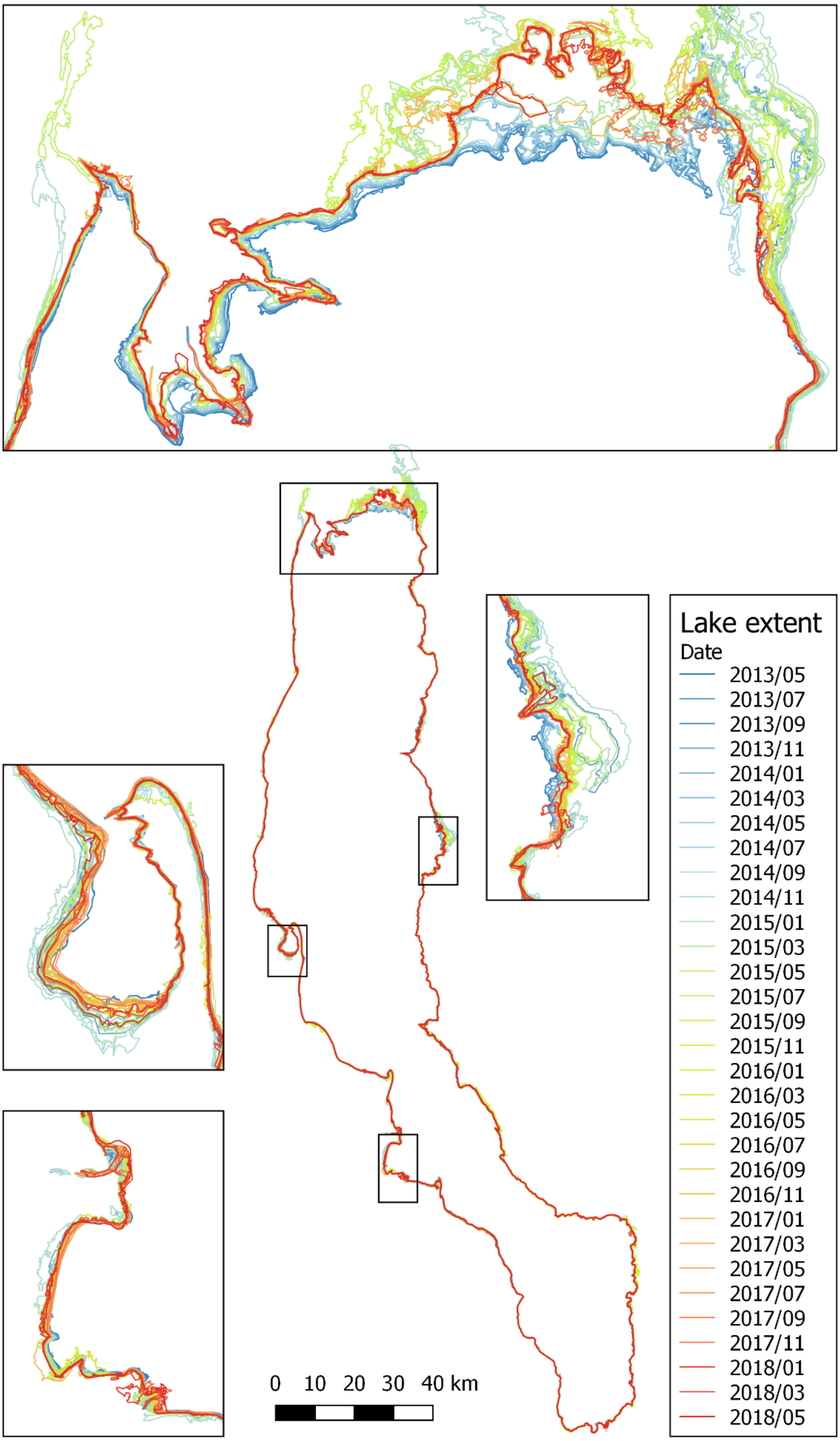

Figure 49 - Five-year bi-monthly dynamics in lake extent based on Landsat images (colour gradient from 2013 to 2018). Highlighted are the areas that show high dynamics due to their topography. Clockwise from top are shown details of the areas in rectangles: Omo delta, Allia bay, Turkwel and Kerio delta, Ferguson's gulf.

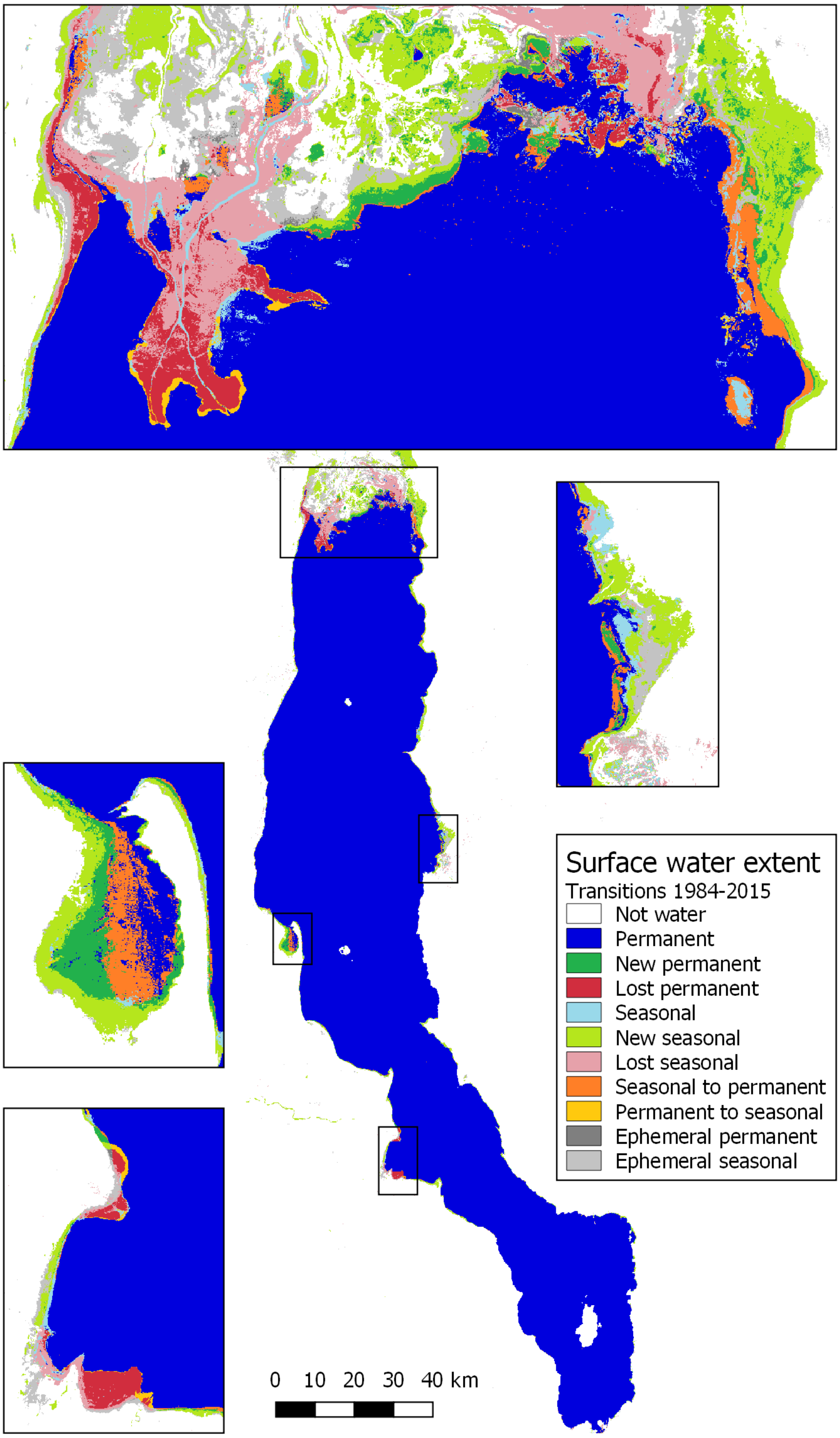

Figure 50 - Lake Turkana surface water transitions between 1984 to 2015 [Pekel et al., 2016].

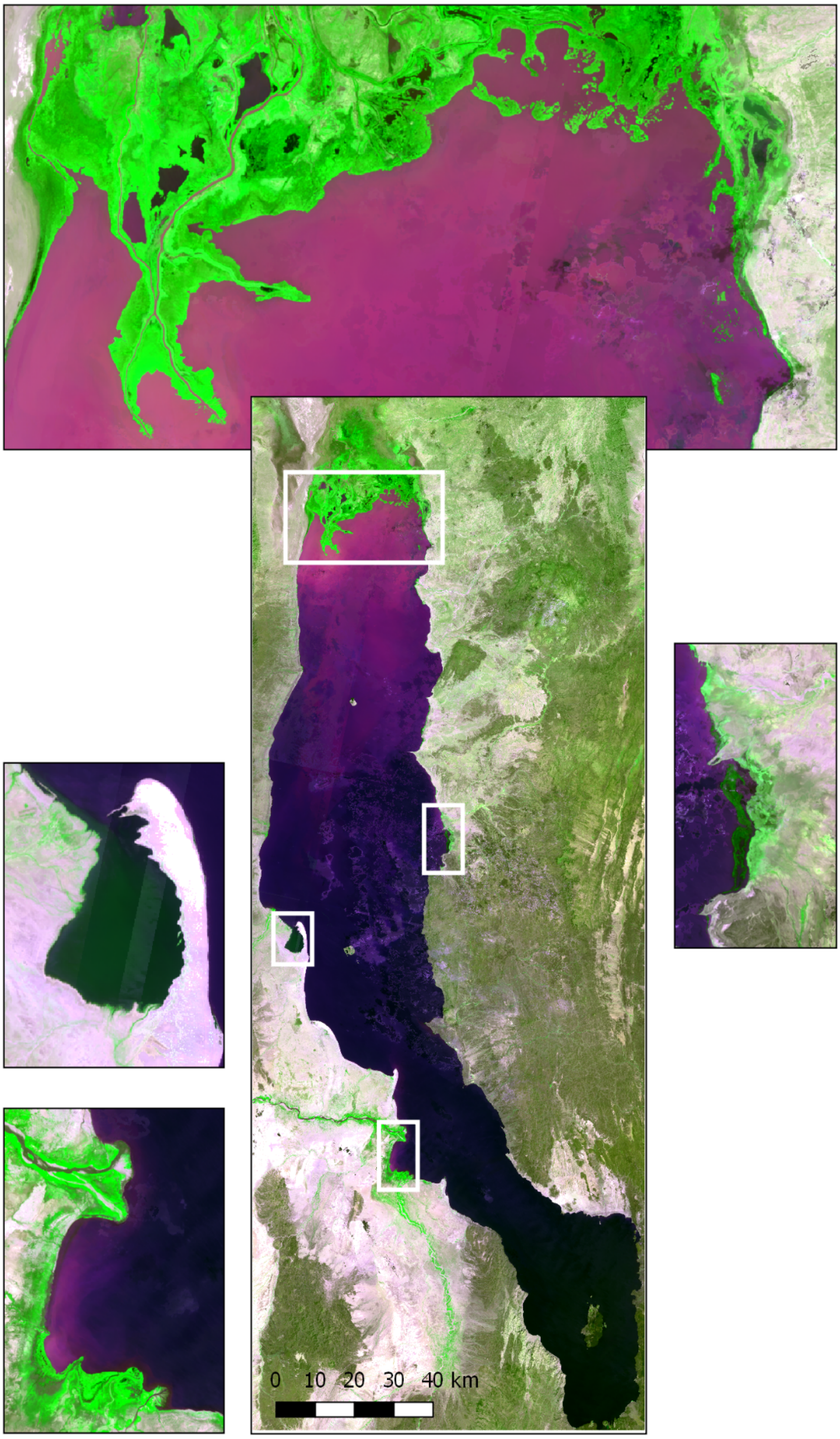

Figure 51 - Current (Jan 2018) extent of lake Turkana shown on a false color Landsat composite (NIR, red and green bands, courtesy of US geological survey). Bright green indicates high photosynthetic activity and thus productivity of wetland vegetation.

Implications for fisheries

River systems with flood pulses are much more productive than river systems with static flows because they support floodplains as aquatic/terrestrial transition zones (ATTZ) that mobilize nutrients from land to water [Junk et al., 1989]. The same is true for lake systems: The magnitude of fluctuations in water levels are positively correlated with fish catch due to nutrient inputs and improved breeding habitats over seasonally flooded lands [Kolding & van Zwieten, 2012]. The relative lake level fluctuation index (RLLF) is composed of the ratio between mean lake level amplitude and mean depth of a lake. The deep, stable Lake Tanganyika has a low seasonal RLLF of 0.13, whereas the shallower Lake Chad has a value of 30.28. Lake Turkana is somewhere in between, with a seasonal RLLF of 3.72 [Gownaris et al., 2018]. No reliable recent figures are available for both catch and effort in Turkana fisheries to estimate the effects of recent variations on fish stocks. Data from the 1980's show a strong linear relationship between deviations of lake levels from long-term mean and annual catch per boat in tons [Kolding, 1992]. Following this relationship, fish catch would decrease 4 tons per boat per year per meter lake level decrease (J. Kolding pers. comm.). The average boat catches about 20 tons of fish per year [Kolding, 1992]. The decrease in average seasonal variation by about 50 cm, observed since 2015 would mean 10% loss of income and/ or food for people depending on fisheries around Lake Turkana. For people who live in poverty, these 10% can represent an existential threat, unless other sources of income and nutrition become available.

Implications for flood recession agriculture

Flood recession agriculture (typically growing sorghum, maize, beans and peas) is of high importance for the food security of pastoralist communities in the lower Omo valley [Yazew et al., 2015; Yntiso, 2012]. Based on high resolution RapidEye satellite imagery, we digitized the cultivated area in temporarily flooded zones along the river for the years 2005, 2008, 2010, 2011 and 2012. We found a strong correlation between the modelled annual discharge variation and flood recession area. A detailed analysis is available in Deliverable 3.5 "Integrated model of the WEF nexus" of the DAFNE project ().

3.4.4 Changes in the Omo delta

The delta of the Omo River draining into Lake Turkana is one of the few deltas in the world that are still undergoing largely unrestricted ecological dynamics. Compared to the surrounding desert areas, the Omo Delta is densely populated, as it provides an important year-round refuge for agro-pastoralist communities. Flood recession agriculture, lifestock grazing and fisheries are the most important ecosystem services that are threatened by environmental changes following the construction of the Gibe 3 hydropower dam upstream of the Omo River that started operating in 2015.

The comparison of the lake extent over time (Figure 53 A) reveals that the delta has been shrinking rather than growing over the past years, despite generally decreasing lake levels. This might be associated with reduced sediment loads since closure of the Kuraz sugar dam in 2012 and Gibe III in 2015. Without constant deposition of sediment, the delta will be washed away by occasional high waters or even by the waves that build up over the lake due to the constant wind from a southerly direction [Schuster and Nutz, 2018].

The Lower Omo River is still widely free flowing. That means it constantly changes its' bed as the result of the interaction between hydrological and geomorphological processes. This becomes most apparent in the delta, where the river drains into Lake Turkana and deposits huge amounts of sediment. Decadal flood events have in the past completely overturned the entire delta and its' wetlands. This can be catastrophic for humans who have their livelihoods in the riparian areas, frequently causing deaths from drowning. Yet, such dynamics are ecologically desirable as they create rare habitats for species adapted to these natural disturbance processes. In addition, the lake ecosystem might benefit from these processes due to releases of nutrients and the creation of spawning areas for fish. Based on time series of Landsat images, we followed the evolution of the river channel network in the delta from 1972 to 2018 and illustrate a reduction in morphological dynamics in recent years. Although large parts of the delta remain occasionally flooded, the main channel of the Omo River has not changed since 1990. Because of this, the channel is constantly getting longer (Figure 53 B). A dam-induced reduction in seasonal and decadal dynamics could further reduce the occurrence of natural changes in the delta, resulting in the further prolongation of the river channel. This will result in a reduction in connectivity between lake and river by increasing the distances for fishes that migrate upstream. Additionally, we tracked long-term dynamics in land-water interactions coupled with human activities to provide management scenarios for future restoration activities. Using multiple sources of remote sensing time series (Landsat 5/7/8, Sentinel 2, RapidEye), we detected human settlements (Figure 53 C), flood recession agriculture (Figure 53 D) and vegetation classes based on leaf area index (LAI, Figure 53 E).

We found that the delta has been shrinking since 2015 despite a reduction in lake levels during filling of the Gibe 3 reservoir. Dynamics in river morphology declined as the riverbed (and the levees that confines it) showed a consolidation process in the absence of major floods. The vegetation showed LAI reductions in zones dependent on river water and increases in zones closer to the lake. The limitation of flooding events and the trapping of sediment, potentially associated with hydropower production at the Gibe 3 dam, may be the main reasons for the observed pressures on the Omo Delta. Changes in vegetation can be explained by gradual intrusion of salty water from the lake and associated proliferation of the invasive shrub *Prosopis juliflora*, as we observed in the field (Figure 52). Both processes lead to a reduction in suitable areas for agriculture and grazing activities.

Figure 52 – Area in the southern part of the delta that is dominated by invasive *Prosopis juliflora* shrubs (picture; F. Kleinschroth).

3.4.5 Changes in sediment retention

An important impact of the construction of a dam cascade along the Omo river is the alteration of the sediment budget. While an assessment of such impact will be available from the WEF model simulating the implementation of different reservoir management policies, a preliminary assessment of changes in sediment retention was carried out[2] by means of a model-based assessment of sediment production, retention and transfer, also accounting for the designed dead storage in the built reservoirs. The numerical model experiment provided spatial estimates of the value of total sediment export, and spatial estimates of sediment retention, both in the case of natural condition and in that of impounded river. The former can be considered a biophysical expression of sediment retention services provided by the landscape, the latter an estimate of what fraction of the sediment retention service is still possible, especially downstream of dams.

[2] Work in progress by WLRC, Ethiopia

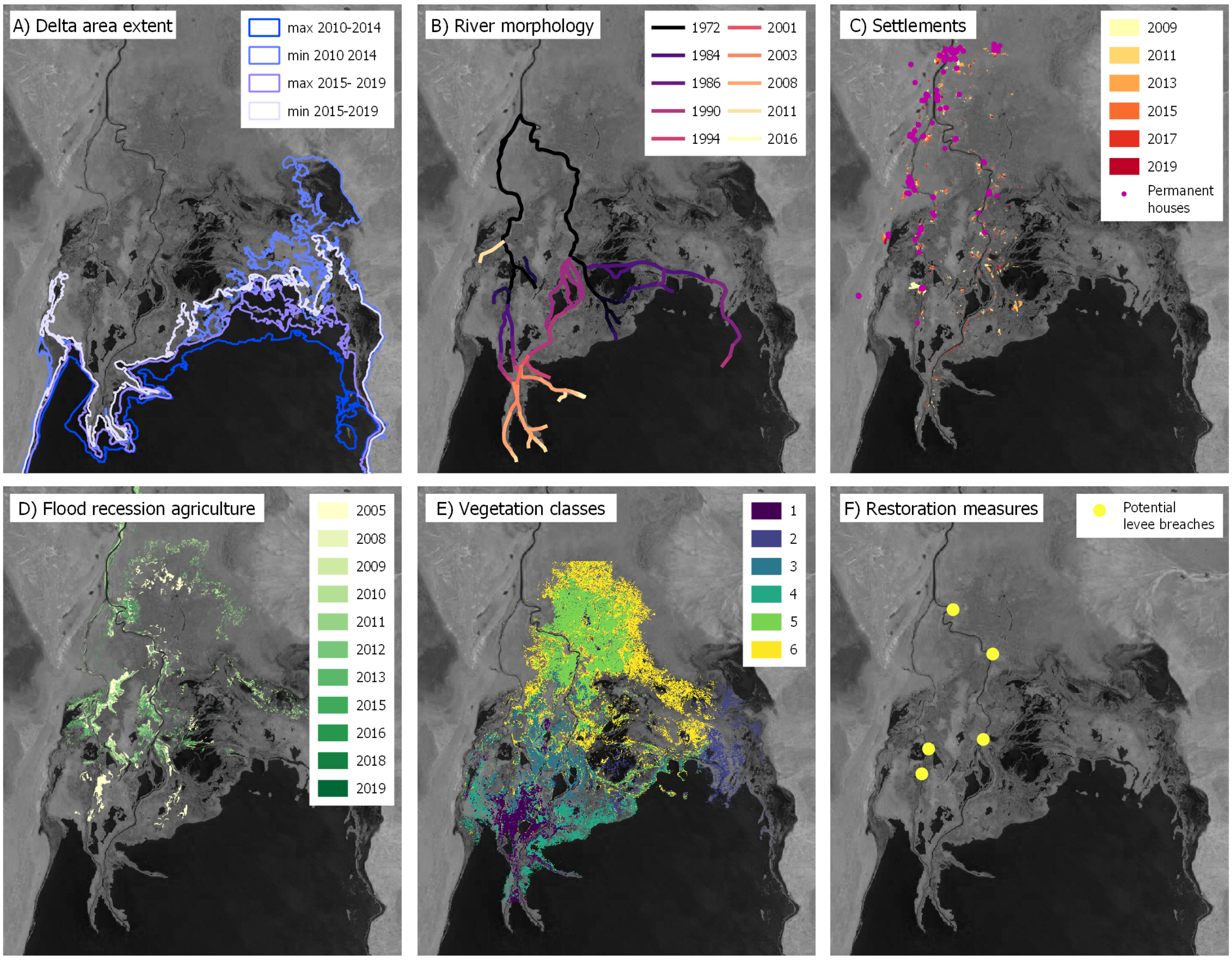

Figure 53: Change analysis in the Omo Delta over time. A) Delta area extent, B) Development of river channels from 1972 to 2019., C) Settlements and permanent houses from 2009 to 2019 (analysis by S. Amos[3]), D) Flood recession agriculture from 2005 to 2019 (analysis by F. Semeria[4]), E) Vegetation classes based on leaf area index (LAI) between 2015 and 2019 (data from VISTA remote sensing), F) Potential locations for artificial levee breaks to restore flooding dynamics.

The preliminary simulation results (Figure 54 and Figure 55) showed that the total sediment exported high along the entire Omo-Gibe river system and maximum in the lower course of the Omo river. Similarly, the total sediment retained is the largest the middle section of the Omo riverand 50% of the largest values in the extreme northern and eastern parts of the upper Omo.

These results potentially provide a useful link between the development of sustainable basin management pathways and their implementation into the WEF model, to assess the availability of sediment related ecosystem services. For instance, a reduction of sediment export from the upper catchment by increasing forest cover and by erosion control measures can be a positive outcome for soil conservation, people who depend on it for agriculture and avoided cost of removal of sediment accumulated in reservoirs. The trapping of sediment behind dam walls presents a major threat to the quality of downstream ecosystem services. The sediment that is transported down from the Ethiopian highlands is an important component of the fertility of the lower Omo Valley and even the survival of the Omo Delta. Indeed the observed current shrinkage of the Omo Delta may be a direct result of reduced sediment availability, mainly because of the reservoir sediment trapping.

[3] Digitized from RapidEye satellite imagery as part of a BSc thesis at ETH Zurich

[4] Digitized from RapidEye satellite imagery as part of an MSc thesis at Politecnico di Milano

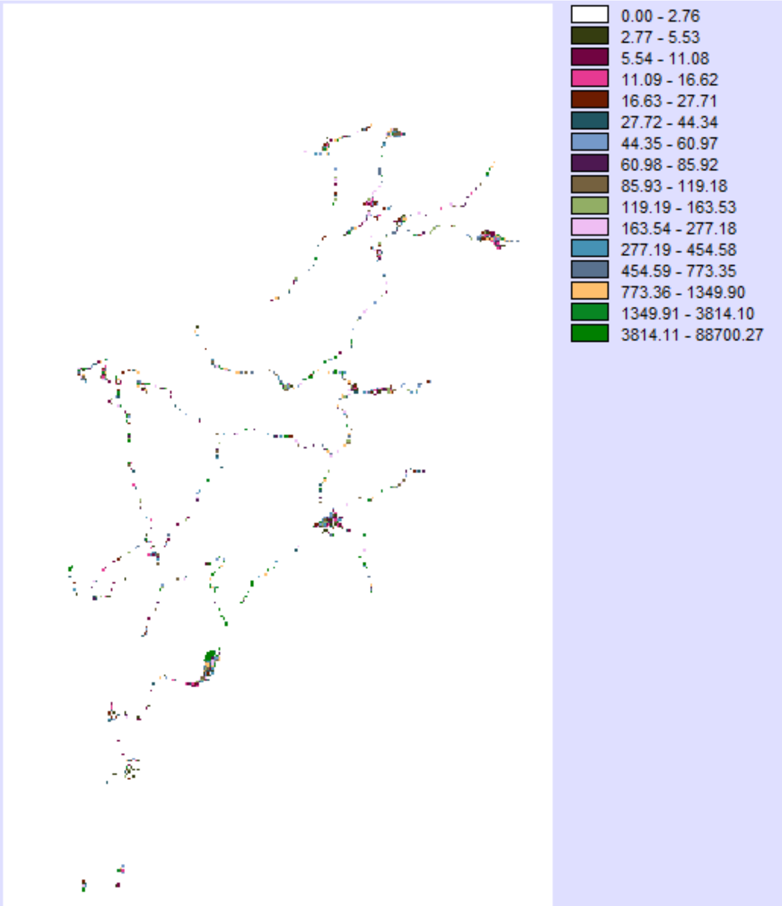

Figure 54 - Simulated total sediment export per pixel (preliminary results in tons)

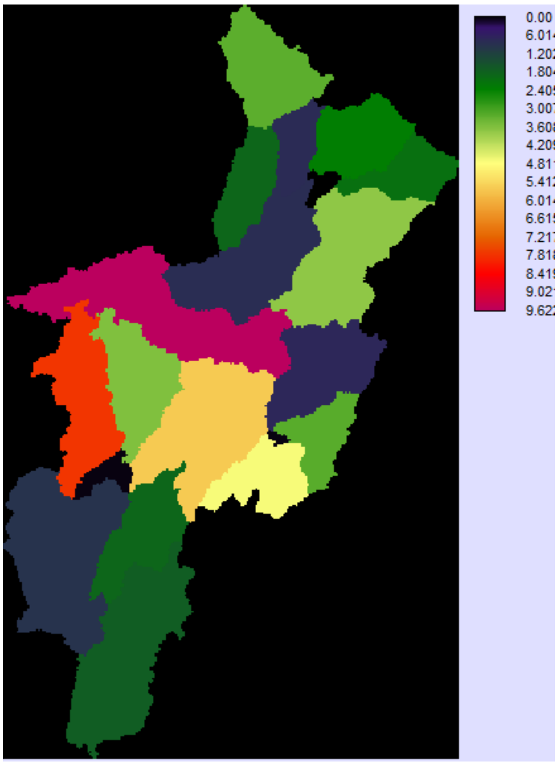

Figure 55 - Simulated total sediment retained by sub-watershed- dredging adjusted (preliminary results in tons)

3.5 ECOSYSTEM MANAGEMENT PATHWAYS

Increasing and conflicting demands for ecosystem services make it increasingly necessary to replace the self-regulating properties of ecosystems with management decisions. Such decisions are typically based on technical approaches that apply simple formulas to estimate sustainable uses of single entities (such as water). Yet, as Defries and Nagendra (2017) highlight, ecosystems are extremely complex and do not allow prediction of all consequences of interventions across spatial, temporal and administrative scales. Therefore, Ecosystem management needs to be approached as a "wicked" problem that doesn't have a single solution. Ecosystem management must avoid two traps: a) falsely assuming a tame solution and b) inaction from overwhelming complexity [Defries & Nagendra, 2017]. With this in mind, we propose multiple pathways for ecosystem management, based on the indicators for ecosystem services outlined so far that need to be adapted to the local conditions and demands of stakeholders.

3.5.1 Reservoir Release Strategies (Environmental Flows)

Traditionally, environmental flow requirements have been imposed on dam operations in the form of release of a minimum flow. Yet, this typically does not account for varying flow regimes with flood pulses in order to provide best natural-like conditions for aquatic ecosystems. Demand curves for environmental goods and services are needed for a reservoir optimization model [Tilmant et al., 2010].

High flow scenarios

The environmental flow releases for Gibe III dam suggested in the Environmental Impact Assessment [EEPCO, 2009] are oriented at a value of 1200 m^3/s, which is below the mean annual maximum (Figure 56, Figure 57). This approach will guarantee certain services such as providing spawning cues to fishes and maintaining light flooding dynamics, but it will not allow for an occasional system renewal triggered by occasional extreme flood peaks. Releasing more destructive floods will be difficult to justify due to the potential risk for lifes and houses built in riparian zones. In addition to simulated annual flow peaks, we suggest that a healthy ecosystem also requires extreme peaks to occur every 10 years or less. Environmental flow release strategies should include the flexibility to forward occasional highs and lows in precipitation in their full extent to the downstream ecosystems. This requires a very sophisticated warning system so that people have enough time to move out of the way.

Low-flow scenarios

While flow-management strategies are commonly centred around minimum flow requirements and flood releases, it is often overlooked that river catchments in strong seasonal climates also have periods of low-flow. These are important phases for example for people to use temporarily inundated areas, without getting their feet wet.

Yet, year-round hydropower production leads to constant releases of the same amounts of water through the turbines, resulting in highly unnatural discharge patterns. The only solution to this is to reduce or completely stop production of electricity in periods of drought. Fortunately, these typically coincide with seasons of high wind and sun radiation. Ideally, dam projects should therefore be accompanied with the installation of wind turbines and solar-power plants to buffer periods of low flow.

3.5.2 Flood Management

The main take-home-message of this deliverable is that maintenance of seasonal flow variation provides services such as wetland preservation, flood recession agriculture and fish breeding. However, the other (well-known) side of the medal is that flooding not only provides services but also disservices to people. Depending on the demographic development in the study regions, it is likely that floods will increasingly be perceived as a threat to the lives and properties of people.

Resource-reliant poor people are commonly the most vulnerable to natural disasters. Once dams are built, the operators take over a strong ethical responsibility in preserving downstream populations from damages and they can only to some extent refer to "natural" dynamics anymore. Therefore, flood releases for environmental purposes cannot ignore the risks to local residents and need to be embedded in the social context. Making communities resilient to flooding, e.g. through better knowledge of where potentially inundated areas are, needs to have a higher political priority than simply promising the full protection from floods through dam construction as it is currently the case for Gibe III [EEPCO, 2009].

Risks can be reduced by stepwise release of water and warning systems to downstream riparian populations. As shown in Europe and elsewhere, targeted restoration of wetland areas can help with the retention of dangerous floods. For species conservation, it is additionally very important to align the timing of the floods for example with the breeding season of birds. This needs to be informed on a year-by-year basis.

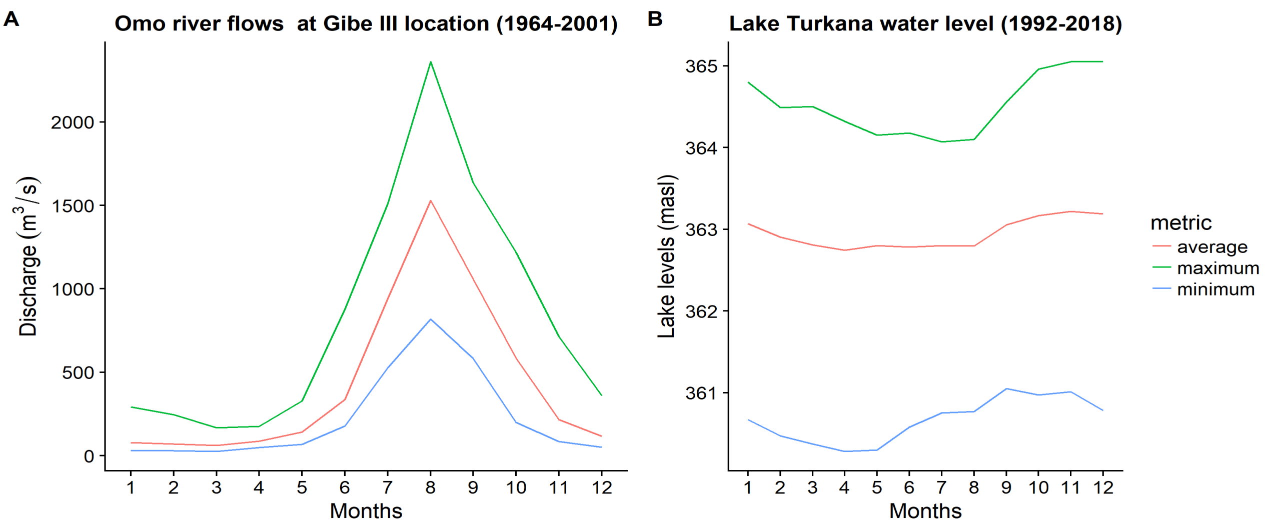

Figure 56 – Long-term variability for A) flow of the Omo river at the Gibe III dam location 1964-2001 [EEPCO, 2009] and B) Lake Turkana water levels 1992 – 2018 [Crétaux et al., 2011], each summarized as average, minimum and maximum values.

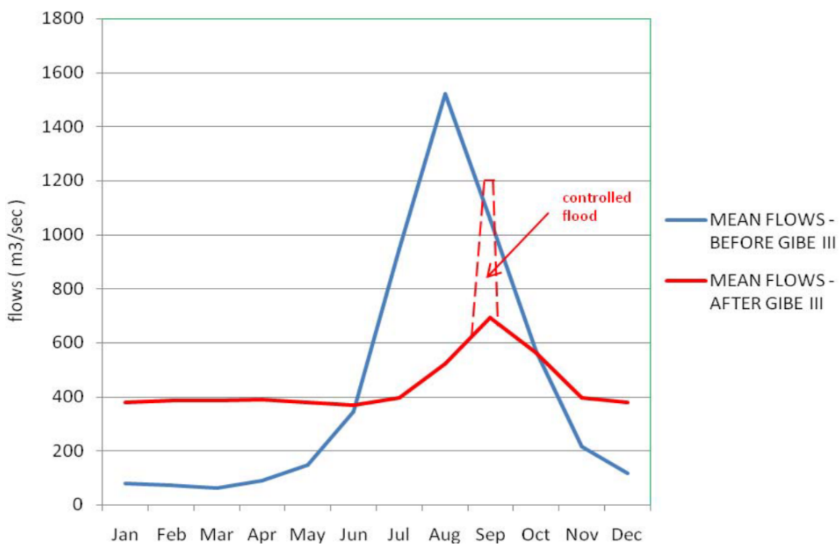

Figure 57 – Monthly flows at Gibe III site: mean flows 1964-2001 (blue), projected mean flows after dam closure (red) with suggested controlled flood releases (dashed line). Source: [EEPCO, 2009]

3.5.3 Maintaining/ Restoring in-Stream Connectivity

Several fish species migrate from Lake Turkana upstream the Omo River for breeding [Kolding et al., 2016]. Any management plan on the catchment scale should therefore make sure to include measures to remove obstacles to fish migration or to provide appropriate deviations. No information is available about how far particular species migrate. Only for *Alestes dentex* it was suggested that it migrates over hundreds of kilometres, with large juveniles entering rivers, achieving growth and maturation in riverine habitats, then continuing their upstream migration as adults in the following years [Hutchings, 2002]. From better studied fish species in other regions it is, however, known that such migrations can lead over hundreds of kilometres. That means the current and planned dams need to be designed in a way that fish can pass up-and downstream.

As described above, fish migration occurs during annual peak flows. These might potentially play an important role in river connectivity as the river channel in the delta gets increasingly longer and might be subject to heavy sedimentation. Regular peak flows might have the important function to flush the river channel and connect flooded habitats.

3.5.4 Artificial breaches in the river bank

Especially in the Omo delta, people depend on areas that are temporarily inundated through river flooding. This function cannot be replaced by water from the Lake due to the high salt content that only supports the growth of salt-resistant plants. Over time, sedimentation along the two river branches that pass through the delta have developed levees on both sides. Only occasional floods surpass or break the levees, creating desirable flooding dynamics. Yet, dam-related flow equalizations prevent such extreme events, leading to water directly draining into the lake without previously flooding the delta. As a concrete restoration measure, we suggest artificial levee breaches to secure freshwater-dominated zones in the delta for ecosystem services delivery. We identify five potential locations for such breaches (Figure 53 F), based on historical channels in the delta. Restored floods will target hotspots of flood recession agriculture and grazing, but spare the locations of more permanent settlements. Timing of the breaches should be stacked to avoid all areas being flooded at the same time.

3.5.5 Sediment Management

To reduce negative effects on downstream livelihoods and ecosystems from “sediment starvation” downstream of dams, the continuity of sediment transport needs to be restored. Measures can typically be described by “Store the clear water and release the muddy.” Kondolf et al. (2014) generally differentiate between methods to route sediment through or around the reservoir and methods to remove (or flush out) sediments accumulated in the reservoir to regain capacity. This sediment can then be released to the downstream river. While the first type of method needs to be implemented during the design phase of the dam, the second type can be used for existing dams, although it is costly and can have negative downstream impacts due to the abrupt release of huge amounts of sediment.

Other sediment management approaches simply aim to minimize the amount of sediment arriving to reservoirs from upstream for example by erosion control through forest management.

3.5.6 Forest and Land Cover Management

To control erosion and catchment areas, but also to maintain livelihoods and biodiversity, measures are necessary to limit unsustainable forest uses and clearing for agriculture. Forest management includes regulation but at the same time valuation of logging and the use of non-timber-forest products as an alternative to clearing for agricultural uses. In the Omo-Turkana basin, the overall trend already shows a recovery of forest and grassland coverage. This trend is likely to be associated with short-term climatic effects. Given that these are not stable and are likely to become more extreme in the future, measures are necessary to make ecosystems and the people who depend on them more resilient. Protection of remaining intact forests in the upper catchment such as the Kafa Biosphere reserve therefore remain of high importance. Forest degradation is closely linked with the use of firewood and charcoal production. This is in part because electricity is either not available or the prices are too high in most African countries. Forest use is therefore part of the WEF nexus in that different sources of energy are directly or indirectly linked to each other.

4. CONCLUSIONS

Our review of ecosystems and ecosystem services in the ZRB and OTB highlights far-reaching changes in both demand and delivery of ecosystem services. A few concluding remarks from the overall analysis:

- River modifications have shaped the ZRB starting already more than 50 years ago, a development that is still relatively new in the OTB. In both basins fisheries, flood recession agriculture and grazing grounds are affected by these modifications. The combined effect of lacking decadal floods, reduced seasonal water level variation, and overall reduced water availability pose an imminent threat to livelihoods.
- Most people are able to change their behaviors. That means, also the demand and need for ecosystem services changes over time in interaction with the environmental conditions.
- **Urbanization** through rural-urban migration and wider access to infrastructure strongly shapes the way people use ecosystem services. For example the provision of electricity can take pressure off forests as the demand for firewood and charcoal is reduced. Irrigation agriculture can increase yield per area and thus reduce the overall amount of farmland with positive outcomes for sediment retention through vegetation cover on abandoned fields.
- Urban areas are particularly adaptive to environmental changes and associated changes in availability of ecosystem services. Through trade and transport, commodities, energy and water supply can be satisfied from remote sources, thus increasing the radius in which ecosystem services can be provided. Only a widespread degradation of ecosystems (which we did not detect) will affect urban areas on the long run, due to overall scarcity of ecosystem services.
- In contrast, marginalized communities, such as pastoralist tribes in the Lower Omo Valley, but also **rural** populations in more remote parts of the ZRB often lack the capability and opportunities to adapt to new conditions and are most affected by environmental changes. They may be less in numbers than those who benefit from economic development, but, for marginalized communities, ecosystem services mean more than a monetary value but rather an existential underpinning of their way of life.
- Dam constructions clearly have winners and losers and monetary comparisons will not be able to capture the trade-offs between urbanized development trajectories and traditional pastoralist lifestyles, as the latter may not even be part of a monetary system.
- Behavioral changes can also lead to people giving up lifestyles that are adapted to natural dynamics. Once more permanent settlements are built in former floodplains, the trade-offs between the benefits and the risks of floods become so strong that it is quasi impossible to revert back to pre-dam conditions.
- With changing land uses and settlement patterns also the environmental challenges shift. Invasions of exotic species are often a direct reaction to human induced environmental changes such as water pollution from urbanized areas in the case of floating vegetation invasions.
- Impact mitigation should include ongoing work on timing and control of filling of planned dams such as Koysha, as well as on potential environmental flow releases. To restore some localized flood events in the Omo delta, additional measures such as artificial levee breaks need to be considered, to ensure some flooding and allow local populations to continue using these areas before soil salinity becomes too high.
- To support the integration of all actors in the wider landscape, transfrontier protected areas or UNESCO biosphere reserves would provide viable pathways to foster collaboration and transparency as the cornerstones of adaptive ecosystem management.

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