Fisheries Assessment and Trophic Modelling of Tono, Bontanga and Golinga Reservoirs, Ghana

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Abstract

Man-made reservoirs are important inland ecosystems that provide food and livelihoods in many countries. Due to the dispersed nature of inland fisheries, most individual systems are rarely adequately assessed or monitored, therefore reliable data on the target stocks are largely unavailable to implement management strategies. This thesis focuses on Tono, Bontanga and Golinga reservoirs in northern Ghana which contribute significantly to food nutrition and community livelihoods. The thesis presents studies that demonstrate how differences in reservoir use patterns, reservoir morphometry and physicochemical characteristics influence ecosystem structures and fisheries resource productivity. The thesis includes (i) an assessment of empirical models for reservoir harvest estimations, (ii) a study relating morphometric characteristics of the reservoirs to fish production, (iii) assessments of the exploitation levels and stock status of the reservoirs' target species and (iv) a holistic description of the reservoirs' biological interactions through a food web modelling approach (Ecopath with Ecosim). To improve the estimation of current harvest potential of West African reservoirs, the relationship between total annual fish catch and reservoir surface area was modelled, which compared to a previous model, indicated that catches from reservoirs in the region have more than doubled over the last two decades. While the analysis indicated that fisheries productivity is inversely correlated with both mean depth and surface area, no significant correlation was found with reservoir age. The exploited resources in the small-scale fisheries of the Tono, Bontanga, and Golinga reservoirs were assessed based on length frequency samples. Growth, mortality, exploitation status, stock size, and relative yield per recruit reference points were determined using bootstrapping fish stock assessment (BFSA), a novel framework that allows for the estimation of uncertainties around the life-history parameters and reference levels (e.g., $L\infty$, K, and $F_{0.1}$). A complementary assessment approach based on length-based indicators was used to calculate the species' spawning potential ratios under the current exploitation regime. Tono, Bontanga and Golinga reservoirs provide a total fish catch of 10.1, 15.5 and 17.1 t km^{-2} yr^{-1}, respectively. The reservoir fisheries are dominated by two cichlid species (*Sarotherodon galilaeus and Oreochromis niloticus*). The cichlid species *Oreochromis niloticus*, *Sarotherondon galilaeus*, and *Coptodon zillii* were found to be heavily exploited in all three reservoirs. The giraffe catfish, *Auchenoglanis occidentalis* was found only in Tono and Bontanga reservoirs. In Bontanga, the catfish stock is fully exploited. While in Tono, the giraffe catfish is underexploited, the current fishing mortality could be doubled to increase yield. The length-based indicators suggested all the species at Bontanga and *O. niloticus* and *S. galilaeus* populations at Golinga have spawning stock biomasses below 40% of the unfished biomass. This points to a situation of a possible ongoing recruitment overfishing of those species in the two reservoirs and suggests that a further increase in fishing effort is not advisable. To support the construction of reservoirs' food web models, a study was conducted on the feeding characteristics of the giraffe catfish with the expectation that the population in Reservoir Tono, which has an extensive macrophyte coverage, feeds more on plant material and associated insects than their counterparts in the Reservoir Bontanga. The study showed that fish food items did not differ significantly between the two reservoirs. Insect larvae and algae dominated the stomach contents. Comparative analysis of the reservoirs showed interesting differences: the mean trophic level of the catch was lowest in the largest and deepest reservoir (Tono), likely due to higher trophic level species occupying less accessible deep 'refuge' habitats. In the medium-sized (Bontanga) and small shallow (Golinga) reservoirs, in contrast, a larger catch portion resembles high trophic level species. Lake Bontanga differs from the other reservoirs by having a lower human population impact, a significantly lower Total Primary Production to Total Respiration ratio, a higher Total Biomass to Total System Throughput ratio, a higher Finn Cycling Index, a higher Detritivory to Herbivory ratio as well as the highest gross efficiency of the catch, all indicative for a more developed ecosystem. The smallest shallow (Golinga) reservoir is more impacted by anthropogenic activities than the other two reservoirs as indicated by the high levels of dissolved organic carbon, total dissolved nitrogen bonded, nitrite-nitrogen and turbidity in the reservoir. While the smallest lake had the highest fish production (per unit area) under optimal conditions of water supply, it is most vulnerable when used for both irrigated agriculture and fisheries production. The findings of this thesis suggest that the use of man-made lakes and respective catchment areas should be assessed and managed carefully to prevent the loss of nutrition and livelihoods contributions. Finally, this thesis serves as a broad template for the development of sustainable ecosystem-based management measures not only for the three studied ecosystems but for other reservoirs exposed to human activities around the world.

Keywords: bootstrapping fish stock assessment (BFSA), fisheries production, Ghana, harvest potential, livelihoods, physicochemical characteristics, reservoir morphometry, resource productivity, sustainable ecosystem-based management.

Zusammenfassung

Künstliche Standgewässer sind wichtige Ökosysteme, die in vielen Ländern Nahrung und Lebensgrundlage bieten. Aufgrund der weiträumigen Verteilung der Binnenfischerei werden die meisten Einzelsysteme nur selten angemessen bewertet oder überwacht, weshalb zuverlässige Daten zu den Zielbeständen für die Umsetzung von Bewirtschaftungsstrategien größtenteils nicht verfügbar sind. Diese Arbeit konzentriert sich auf die Seensysteme Tono, Bontanga und Golinga im Norden Ghanas, die wesentlich zur Ernährung und zum Lebensunterhalt der Bevölkerung beitragen. Diese Dissertation präsentiert Studien, die aufzeigen, wie Unterschiede in den Nutzungsmustern, der Gewässermorphometrie und den physikochemischen Eigenschaften die Ökosystemstrukturen und die Produktivität der Fischereiressourcen beeinflussen. Die Dissertation umfasst (i) eine Bewertung empirischer Modelle für Ertragsschätzungen in künstlichen See, (ii) eine Studie, die die morphometrischen Eigenschaften der Seen mit der fischereilichen Produktion in Verbindung setzt, (iii) eine Bewertung des Bewirtschaftungsniveaus und des Bestandsstatus der Zielarten und (iv) eine holistische Beschreibung der biologischen Wechselwirkungen der Seensysteme durch Modellierung der Nahrungsnetze (Ecopath mit Ecosim). Um die Schätzung des aktuellen Fischereipotenzials westafrikanischer künstlicher Gewässer zu verbessern, wurde das Verhältnis zwischen dem jährlichen Fischfang und der Oberfläche der Seensysteme modelliert, was im Vergleich zu einem früheren Modell darauf hindeutet, dass sich die Fänge aus künstlichen Seen der Region in den letzten beiden Jahrzehnten mehr als verdoppelt haben. Während die Analyse ergab, dass die Produktivität der Fischerei sowohl mit der mittleren Tiefe als auch mit der Gewässeroberfläche invers korreliert, wurde keine signifikante Korrelation mit dem Alter der Seen gefunden. Die in den Kleinfischereien der Tono-, Bontanga- und Golinga-Seen genutzten Ressourcen wurden anhand von Stichproben der Längenhäufigkeit bewertet. Referenzwerte für Wachstum, Mortalität, Bewirtschaftungsniveau, Bestandsgröße und den relativen Ertrag pro Rekrut wurden unter Verwendung der Bootstrapping-Fischbestandsbewertung (engl. *bootstrapping fish stock assessment*, BFSA) bestimmt, einem neuartigen Ansatz, der die Schätzung von Unsicherheiten in Bezug auf die Lebensverlaufsparameter und Referenzwerte ermöglicht (z.B. $L\infty$, K und $F_{0.1}$). Ein ergänzender Bewertungsansatz, der auf längenbasierten Indikatoren beruhte, wurde angewandt, um die Laichpotentiale der Arten unter dem gegenwärtigen Nutzungsregime zu berechnen. Die Seen Tono, Bontanga und Golinga ermöglichen einen Gesamtfang von 10,1, 15,5, respektive 17,1 t km^{-2} yr^{-1}. Die Binnenfischerei wird von zwei Buntbarscharten (*Sarotherodon galilaeus* und

Oreochromis niloticus) dominiert. Es wurde festgestellt, dass die Cichlidenarten *Oreochromis niloticus*, *Sarotherondon galilaeus* und *Coptodon zillii* in allen drei Seen stark befischt sind. Der Augenfleckwels (*Auchenoglanis occidentalis*) wurde nur in den Seen Tono und Bontanga vorgefunden. Im Bontanga-See wird der Welsbestand voll befischt. Während im Tono-See der Augenfleckwels unterfischt ist, könnte dort die derzeitige fischereiliche Sterblichkeit verdoppelt werden, um den Ertrag zu steigern. Die längenbezogenen Indikatoren deuten darauf hin, dass alle Arten im Bontanga-See, sowie die Populationen von *O. niloticus* und *S. galilaeus* im Golinga-See, Laichbestandsbiomassen unter 40% der nicht gefischten Biomasse aufweisen. Dies deutet auf eine mögliche anhaltende Rekrutierungsüberfischung dieser Arten in den beiden Seen hin und legt nahe, dass eine weitere Steigerung des Fischereiaufwands nicht ratsam ist. Um die Entwicklung von Nahrungsnetzmodellen für künstliche Seensysteme zu fördern, wurde eine Studie zur Ernährung des Augenfleckwels durchgeführt, mit der Annahme, dass die Population im Tono-See, der einen ausgedehnten Makrophytenbewuchs aufweist, sich mehr von Pflanzenmaterial und damit verbundenen Insekten ernährt als die Vergleichspopulation im Bontanga-See. Die Studie zeigte, dass sich die Nahrungsbestandteile zwischen den beiden Seen nicht signifikant unterschieden. Insektenlarven und Algen dominierten den Mageninhalt. Eine vergleichende Analyse der Gewässer ergab interessante Unterschiede: Das mittlere trophische Niveau des Fangs war im größten und tiefsten See (Tono) am niedrigsten, was wahrscheinlich darauf zurückzuführen ist, dass Arten höherer trophischer Ebenen weniger zugängliche, tiefere „Zufluchtsorte“ aufsuchen. Im Gegensatz dazu setzt sich ein größerer Fanganteil im mittelgroßen (Bontanga) und im kleinen, flachen See (Golinga) aus Arten höherer trophischer Ebenen zusammen. Der Bontanga-See unterscheidet sich von den anderen Gewässersystemen durch einen geringeren anthropogenen Einfluss, ein signifikant geringeres P/R-Verhältnis, ein höheres Verhältnis von Gesamtbiomasse zu Gesamtsystemdurchsatz, einen höheren *Finn Cycling Index* sowie einen höheren Anteil von Detritivoren zu Herbivoren, als auch die höchste Bruttoproduktion der Fänge, alles Anzeichen für ein stärker entwickeltes Ökosystem. Der kleinste und flachste See (Golinga) ist stärker von anthropogenen Aktivitäten beeinflusst als die beiden anderen Gewässer. Dies wird durch die hohen Gehalte an gelöstem organischen Kohlenstoff, gelöstem gebundenen Gesamtstickstoff, Nitrit-Stickstoff und die starke Trübung im Wasserkörper angedeutet. Während der kleinste See bei optimalen Wasserzufluss die höchste Fischproduktion (pro Flächeneinheit) aufwies, ist er am anfälligsten, wenn er sowohl für die Bewässerung der Landwirtschaft als auch für die Fischereiproduktion genutzt wird. Die Ergebnisse dieser Arbeit legen nahe, dass die Nutzung von künstlichen Seen und entsprechenden Einzugsgebieten sorgfältig bewertet und verwaltet werden sollte, um den Verlust von Nahrungsmitteln und Lebensgrundlagen zu verhindern. Schließlich dient diese Dissertation als umfangreiches Muster für die Entwicklung nachhaltiger, ökosystembasierter Managementmaßnahmen, nicht nur für die drei untersuchten Ökosysteme, sondern auch für andere künstliche Standgewässer weltweit, die menschlichen Aktivitäten ausgesetzt sind.

Schlagwörter: bootstrapping fish stock assessment (BFSA), Fischereipotenzial, Fischereiproduktion, Ghana, Gewässermorphometrie, Lebensgrundlage, nachhaltiges ökosystemgestütztes Management, physikochemische Eigenschaften, Ressourcenproduktivität.

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List of Abbreviations

Abbreviation	**Description**
a	Constant of length-weight relationship
APL	Average path length
b	Exponent of length-weight relationship
B	Biomass
C	Catch
CA	Cohort Analysis
CPUE	Catch per unit effort
Chl-*a*	Chlorophyll a
D:H	Detritivory to herbivory ratio
E	Exploitation rate
EE	Ecotrophic efficiency
ELEFAN	Electronical LEngth Frequency ANalysis
ELEFAN_GA	ELEFAN with genetic algorithm
EwE	Ecopath with Ecosim
F	Instantaneous rate of fishing mortality
FAO	Food and Agriculture Organization
FISAT	FAO-ICLARM Stock Assessment Tools
FCI	Finn’s cycling index
Fmsy	Fishing mortality rate at MSY
GE	Gross efficiency
K	Curvature parameter of the VBGF
Lc	Mean length of fish at first capture
LFQ	Length frequency data
Lmean	Mean length of catch
L_∞	Asymptotic length
L_m	Length at first sexual maturity
Lopt	Optimum length of capture
LWR	Length-weight relationship
M	Instantaneous rate of natural mortality
MSY	Maximum sustainable yield

MTI	Mixed trophic impact
MTL	Mean trophic level
Φ	phi-prime, i.e., a length-based index of growth performance
P	Production
P/B	Production/biomass ratio
Q	Consumption
Q/B	Consumption per biomass
TB/TST	Total biomass/total systems throughput
TL	Trophic level
TST	Total system throughput
VBGF	von Bertalanffy growth function
VPA	Virtual Population Analysis
yr	Year
Y'/R	Relative yield per recruit
Z	Instantaneous total mortality
ZMT	Center for Tropical Marine Research

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CHAPTER 1: General introduction

1.1 Overview of freshwater fisheries with emphasizes on Ghana

Fisheries are one of many services provided by inland aquatic ecosystems to society. Man-made reservoirs are part of those inland ecosystems, and may either be embedded in a river network or not (Hayes et al., 2017). They are essential for food security and provide livelihoods for people throughout the world. For many low-income groups in developing countries, fish from these systems are the main source of animal protein in their diets. Globally, lakes, reservoirs and wetlands cover a total area of about 7.8 million km^2 and provide a rich environment for inland capture fisheries (De Graaf et al., 2015). Contrary to marine capture fisheries, which have already levelled out in the late 1980ties, capture fisheries in the world's inland waters have grown steadily and produced 11.6 million tonnes in 2016, representing 12.8% of total marine and inland catches (FAO, 2018).

Construction of dams and reservoirs has been driven by economic needs, while ecological consequences have as yet received little consideration. In industrialized countries, construction of reservoirs is slowing down, but in many developing countries it continues at a rapid pace (Miranda, 2001). Although a substantial quantity of the inland fish consumed stems from small inland water bodies, these systems are rarely surveyed and/or assessed as the resources of Government Fisheries Departments are usually very limited (MRAG, 1995). In both the developed and developing world, inland waters suffer from multiple competing demands for water (e.g. hydropower, withdrawal for agriculture, industrial processes or transportation), resulting in management trade-offs between fisheries and those other uses (Welcomme et al., 2010).

The right for food is basic for humankind. However, hunger remains unacceptably widespread. Therefore, food security is among the topmost issues on most international fora like the COP17 of the UNFCCC; it is a priority area in the Rio+20 Zero document and the first thematic area of focus for the New Partnership for Africa's Development (NEPAD). The United Nations Agenda 2030 and its 17 Sustainable Development Goals (SDGs), which aim at a transformation towards resilient societies and environments (UN, 2015), the global importance of food security and fisheries resources (SDG 2 *Zero hunger* and SDG 14 *Life below water*). Despite these discussions and efforts at different levels and fora, nearly one billion people go to bed hungry. The World Food Summit of 1996 defined food security as follows, "food security, at the individual, household, national, regional and global levels [is achieved] when all people, at all times, have physical and economic access to sufficient, safe and nutritious food to meet their dietary needs and food preferences for an active and healthy life". Notwithstanding, inland fisheries including those of reservoirs, which provide the animal protein needs of the most vulnerable populations in sub-Sahara Africa, have not been adequately considered in management and development agendas of most countries.

Ghana's fisheries sector contributes significantly to the nation's economy. Fishing provides a major source of employment, income and food for hundreds of thousands of people in the country. In northern Ghana, fish from rivers, reservoirs and dugouts play a vital role in the provision of protein to the majority of the rural poor in the regions. Domestic demand for fish in Ghana has also been rising in response to growth in human population, income and urbanization. Hence fish and fish products, including low-value fish species like tilapias, are gradually becoming more expensive to the poor, relative to other sources of animal protein. Data from the Fisheries Commission of Ghana covering the years 2010-2017 indicate that production from inland waters contributed between 22% and 31% to Ghana's total fisheries production. The current national demand for fish is estimated at 880,000 t annually, but only close to 50% (420,000 t) is produced locally, leaving a supply deficit of a little over 50% (460,000 t), which is filled in by fish imports worth over US$200 million (MoFA, 2012).

Ghana is comprised of a system of rivers, lagoons and lakes that form the basis of a robust inland fisheries industry. About 10% of Ghana's land surface is covered by water. The main sources of freshwater fish in Ghana are the Lake Volta, reservoirs - originally meant for irrigation and potable water projects - and fish ponds (FAO, 2016c). Ghana's inland fisheries production is dominated by Nile tilapia and other cichlids (Fig. 1.1) (FAO, 2019).

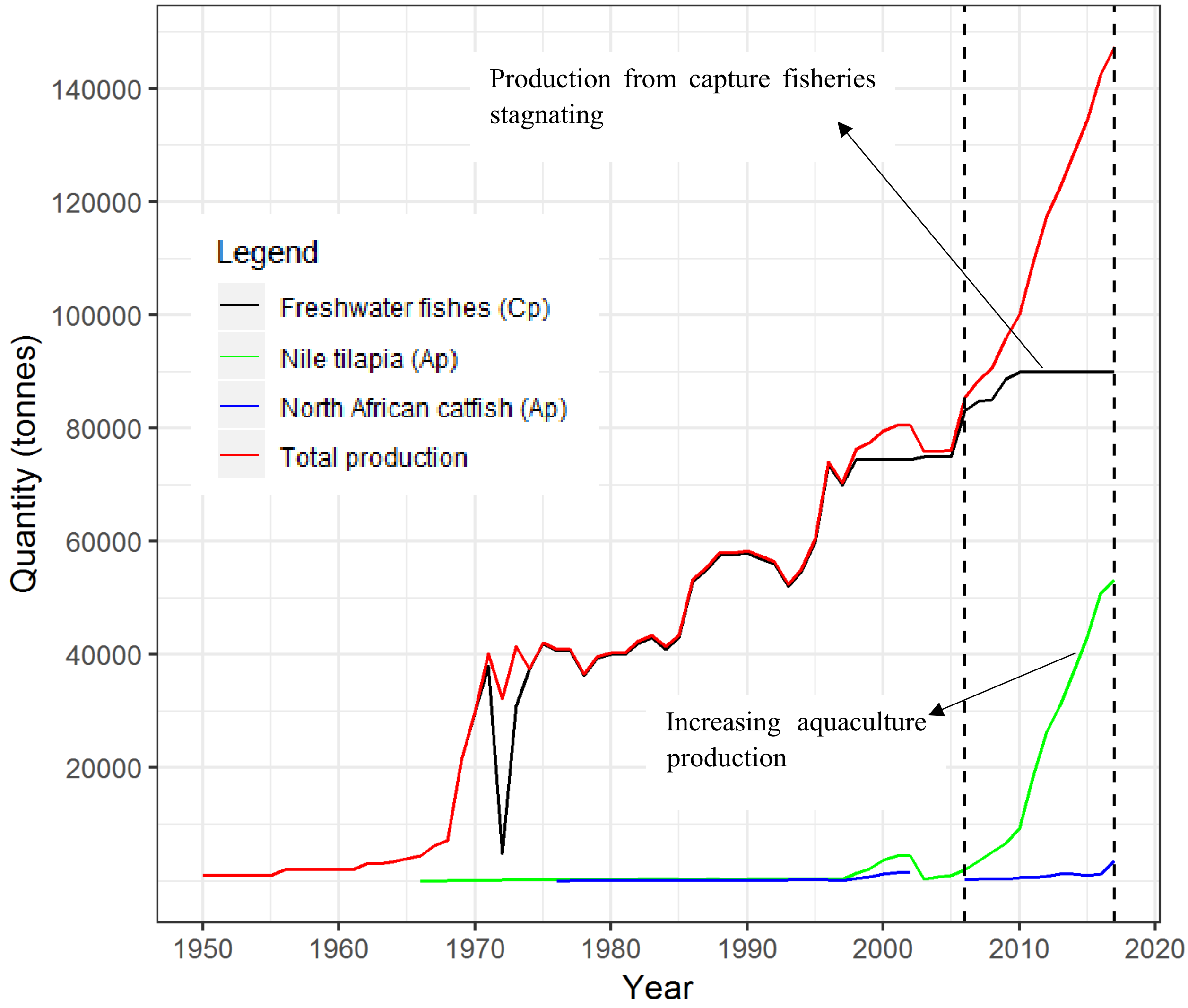

Figure 1.1. Fish catch from inland waters of Ghana from 1950-2017. Total production (red line). Ap and Cp refer to production from aquaculture and capture fisheries sources respectively. Data Source: (FAO, 2019).

Ghana's fish stocks, both marine and freshwater, have been dwindling over the years (FAO, 2016c). Possible reasons for the decline in catches have been attributed to overexploitation of stocks, environmental degradation and low water levels that have negatively impacted fish production (Abban et al., 2000; Amevenku and Quarcoopome, 2006).

The economic returns and other benefits derived from inland waters of Ghana in terms of fish production are insufficient due to limited infrastructure, poor enforcement of fisheries regulations, inadequate research and development, and limited finance and human resources. Moreover, an increasing rate of siltation in lakes, as a result of erosion associated with high rates of deforestation, and declining fish yield have been noted as part of the major environmental issues of freshwater systems in Ghana (World Bank, 2011). The inland fisheries of Ghana are poorly appreciated and are given low priority relative to other competing uses of water. As a consequence, inland fish stocks are not comprehensively monitored or assessed and most of the provisions of the Ghanaian fisheries legislations and regulations are designed for the management of marine and coastal fisheries. Given the marginalisation of Ghana's inland fisheries, important issues are: (i) catch status and trends are not adequately estimated; (ii) total production, economic and societal value of the inland fisheries are largely unknown; (iii) there is no comprehensive strategy for the management of the inland fisheries; (iv) there is limited monitoring of stocks.

Northern Ghana endows numerous freshwater bodies and therewith an enormous potential for inland fisheries development, which still remains largely untapped. This potential contribution is high, if reservoirs are technically and purposefully designed to provide significant and sustainable fish production. However, fish production in these reservoirs is often insignificant due to failures in reservoir designs, bad (unsustainable) fishing practices, inadequate planning and policy, limited research and development. Addressing these issues requires an adequate assessment of the reservoir fisheries resources accompanied by implementation of better policies and management strategies.

Recently, construction of reservoirs has become one of the top developmental agendas in Ghana with plans by the two major political parties in Ghana to revamp existing reservoirs and construct new ones in the five regions of northern Ghana, which is categorised as Savannah agroecological zone with a mono-modal rainfall subject to wide variation. Crop and animal production are therefore challenged due to the intermittent and terminal droughts. To minimize these challenges, reservoirs such as the Tono, Bontanga, and Golinga of this study have been constructed for varied purposes including irrigated agriculture, fisheries, livestock watering, and domestic uses (MoFA, 2018).

Over the years, Tono, Bontanga and Golinga reservoirs have grown into significant inland fishing grounds. Tono reservoir is the largest in the Upper East region of Ghana with a surface area of 1,860 ha. It is the most important source of reservoir fish in the region. In the Northern region of Ghana, Bontanga and Golinga are the most important sources of reservoir fish in the region. Bontanga has a surface area of 670 ha, while Golinga is the smallest of the three with an area of only 62 ha. Bontanga and Golinga are 20 km apart while Tono is approximately 210 km away from Bontanga and Golinga. Golinga has one landing site, Bontanga has two main landing sites (Voggu and Bontanga), and Tono has five landing sites.

The management challenges of reservoir fisheries in Ghana are no different from what has been noted globally for many inland water bodies. In the past three decades, capture fisheries production worldwide has come under intense exploitation to the extent that fisheries production has stagnated and is likely to dip due to pressures from overfishing, habitat degradation, and pollution, all driven by population increases (Allan et al., 2005; Delgado, 2003). One of the consequences is that increase in human population and irresponsible fishing practices make capture fishery landings unable to keep up with the demand, and this has driven prices out of the reach of the poor. Effective management and regulatory measures and rapid production alternatives are urgently needed to ensure sustainable fish supplies locally. In addition to the regulations of fishing for sustainable fisheries, stock enhancement represents a potential component of an economically viable and ecologically sound management strategy to replace extinct stocks for commercial or recreational fishing, to rebuild depleted stocks, and to augment existing but perhaps overexploited stocks (Hilborn, 1998; Leber, 2002; Travis et al., 1998).

Allan et al. (2005) posit that owing to an incomplete understanding of how inland waters function, policymakers and managers often fail to intervene when fisheries are in decline, until the fishery resources have virtually collapsed. Incorporating fisheries into ecosystem approaches for the management of inland waters requires to evaluate fisheries exploitation potential and to examine feedbacks between fisheries, ecosystem productivity and aquatic biodiversity (Beard et al., 2011).

Without fisheries survey data, managers cannot recommend measures to ensure that fish populations are managed sustainably, and without resource inventories, they cannot prioritise allocation of resources for sectoral development. Estimates of potential sustainable fish yields are not only valuable for sound management of existing fisheries, they are also useful when planning and evaluating the likely benefits of constructing new reservoirs for irrigation, electricity generation or domestic water supply (MRAG, 1995). Therefore, the review of published information on fish yields as related to (simple) environmental, climatic and demographic parameters is an important step for estimating the fishery potential of reservoirs in the semi-arid West African region. This contributes to the "Rome Declaration: Ten Steps to Responsible Inland Fisheries" (FAO and MSU, 2016), which among other recommendations, emphasizes the importance of adequate valuation of inland aquatic systems.

Modern fisheries management, as practised since the early 1940s, is strongly based on the ecosystem approach but focuses primarily on fishing activity and target fish resources

(Garcia, 2003). According to Lackey (1999), inland waters are affected earlier and more strongly than marine waters by environmental problems, and management developed as an extension of wildlife management and involves a substantial amount of direct intervention on the habitat and species composition. Ecosystem management is the application of ecological, economic, and social information to achieve a sustainable resource use and the desired social benefits within a defined geographic area and over a specified period (Lackey, 1999). Ecosystem management can also be more comprehensively defined as a management philosophy which focuses on desired states rather than system outputs and which recognizes the need to protect or restore critical ecological components, functions and structures in order to sustain resources in perpetuity (Cortner et al., 1994). The Food and Agriculture Organisation (FAO) principles of an ecosystem approach to fisheries management (Garcia, 2003) take into account explicitly the complexity of ecosystems and the interconnections among its component parts. It requires: (1) definition and scientific description of the ecosystem in terms of scale, extent, structure, functioning; (2) assessment of its state in terms of health or integrity as defined by what is acceptable to society; (3) assessment of threats; and (4) maintenance, protection, mitigation, rehabilitation, etc., using (5) adaptive management strategies.

Ecopath with Ecosim (EwE) (Christensen and Pauly, 1992; Christensen et al., 2000; Polovina and Ow, 1985) is an ecosystem modelling software that can be used to address ecological questions, evaluate ecosystem effects of fishing, model the effect of environmental changes and explore management policy options. The EwE approach has been widely used throughout the world in assessing reservoir fisheries impact, environmental changes and for exploring management strategies (see examples in Table 1.1).

However, our study is the first to assess reservoirs in Ghana using the EwE food web modelling approach (Chapter 6).

Table 1.1. Overview of selected global use of Ecopath modelling approach for assessing fishing impacts, environmental changes and management measures in lake and reservoir ecosystems

Reservoir, Country	Purpose	Reference
Bagré, Burkina Faso	Description of the trophic structures and flow of Bagré reservoir; and assessing the impacts of environmental changes and degradation as well as increase of exploitation on the structure and ecology of the aquatic resources mainly on the fish population.	(Villanueva et al., 2006)
Lake Nakuru, Kenya	Model representations of production and biomass relationships and the trophic functioning of the lake corresponding to two critical periods, i.e. 1972 (high primary productivity) and 1974 (low productivity).	(Moreau et al., 2001)
Koka, Ethiopia	Assessing the impact of an introduced exotic carp species in the Lake Koka ecosystem; and the state of ecological maturity of the system.	(Tesfaye and Wolff, 2018)
Wyra, India	Comparative assessment of possible impact of the fishing ban on overall performance of the whole ecosystem from changes in biomass of main groups; and to compare the trophic interactions of the ecosystem after introduction of closed fishing seasons in the reservoir.	(Panikkar and Khan, 2008)
Itaipu, Brazil	Addressing the possible impacts of fishing on the structure and function of the Itaipu Reservoir in Brazil	(Philippsen et al., 2019)
Lake Võrtsjärv, Estonia	Assessing the importance of bottom-up (prey availability) versus top-down processes (predation, fisheries) in the foodweb structure; and comparing quantitatively the energy fluxes from primary producers and detritus circulating through the foodweb.	(Cremona et al., 2018)
Kelavarapalli, India	Evaluating the role invasive species play in the reservoir ecosystem; and to gain insight into the properties and development status of the ecosystem maturity.	(Khan and Panikkar, 2009)
Pasak Jolasid, Thailand	Quantitative description of the trophic relationships in the reservoir and exploring management strategies of the multispecies fishery.	(Thapanand et al., 2007)
Ayamé, Côte d'Ivoire	Quantifying and describing the structure and trophic relationships in Lake Ayamé.	(Traore et al., 2008)

1.2 Assessment of data-limited inland fisheries

Most inland fisheries of sub-Sahara Africa can be described as data-poor, data-deficient or data-limited. There is no clear distinction between these terms. Each term underscores a fishery that lacks some form of data. According to De Graaf et al. (2015), there are severe constraints in the collection of information on inland fisheries, leading to doubts over the reliability of the available information at the global and regional scales. A major constraint of data collection is the dispersed characteristics of inland fisheries, which makes tie application of traditional approaches difficult (De Graaf et al., 2015). However, Fitzgerald et al. (2018) indicate, albeit inland fisheries can be diverse, local and highly seasonal, data-poor methods from marine systems can also be applied for inland fish stock assessment. The majority of inland fisheries are not licensed, operate at commercial, semi-commercial and subsistence levels, and are widely dispersed along the lengths of all rivers and streams as well as in a variety of waterbodies and wetlands. There are often no centralised landing ports or major markets, where data can be easily collected, and a large part of the catch is bartered locally or consumed by the fisher and his/her household. Moreover, catch size and composition, gears used and the number of fishers may vary greatly among seasons. Therefore, data should ideally be collected several times per year, and over a number of years, but poorly developed infrastructure in remote areas makes data collection both time-consuming and expensive (De Graaf et al., 2015).

Most reservoir fisheries are in regions that lack the human capacity to control catches and fishing pressure. Simple-to-implement measures (e.g., size-based rules) should be the focus for sustainable management of these reservoir fisheries and appropriate sample-based monitoring can improve the present information on inland fisheries (De Graaf et al., 2015). De Graaf et al. (2015) further argue that rapid improvement of available information can be obtained by providing assessment tools to a global community of practitioners.

Alternative approaches include sample-based surveys, using geographic information systems (GIS), global water database and Google Earth (De Graaf et al., 2015). These sample-based fisheries surveys should be based on a well-described sample frame and sound statistical procedures (Caddy and Bazigos, 1985; Cadima et al., 2005; Sparre and Venema, 1998; Stamatopoulos, 2002).

Besides the challenges in data collection, small-scale fisheries managers often lack the capacity to comprehensively analyse fisheries data. The recently developed R package *TropFishR* (Mildenberger et al., 2017) provides an assessment framework, which allows for the robust estimation of uncertainties around the stock parameter estimates (e.g. $L\infty$ and K). It includes enhanced versions of all the functions of the FAO-ICLARM Stock Assessment Tools II (FISAT II) (Gayanilo et al., 2005) with some more recent methods and optimized routines added. The package allows for a stock assessment routine to derive reference levels (e.g. F_{MSY}, $F_{0.1}$) using yield per recruit modelling, which may be based on a single year of length-frequency

(LFQ) data (Mildenberger et al., 2017). This implies that adequate assessment of reservoir fisheries stocks (which rarely have time series data) can be conducted through TropFishR to derive reliable estimates of management reference points. Related to the use of LFQ data, is the use of length-based sustainability reference points for data-limited situations (Cope and Punt, 2009; Froese, 2004). In this thesis, both assessment approaches were used in assessing the target species of the reservoirs (Chapters 4 and 5).

1.3 Research objectives and hypotheses

This thesis aims at 1) providing a complete description, evaluation and classification of the trophic dynamics and fisheries productivity of Tono, Bontanga and Golinga reservoirs ecosystems and 2) simulating sustainable fishing regimes for the reservoirs. Following these aims, the thesis provides baseline information to facilitate sustainable management of the reservoirs' fisheries and thereby the enhancement of food security in northern Ghana. The objectives of the thesis are to:

i. assess the fishery status/exploitation level of target species of Tono, Bontanga and Golinga reservoirs and elaborate management advice for *Auchenoglanis occidentalis, Oreochromis niloticus, Sarotherodon galilaeus,* and *Coptodon zillii*. (i.e. population level assessment).

ii. elucidate the causes for differences in food web structure and fisheries productivity between Tono, Bontanga and Golinga as related to age, morphometric and hydrochemical features of the reservoirs. (i.e. ecosystem/community level assessment).

I hypothesize that (i) Tono, Bontanga and Golinga reservoirs have, due to differences in surface area, shape, mean depth, age, and resource use patterns; specific conditions that generate differences in growth, mortality and exploitation rates of the fishery target (Cichlid) species; (ii) the giraffe catfish (*Auchenoglanis occidentalis*) population in Reservoir Tono, which has an extensive macrophyte coverage, feeds more on plant material and associated insects than their counterparts in Reservoir Bontanga, and that growth conditions are more favourable in Reservoir Tono; and (iii) the lakes' differences in physical features (shape, mean depth, overall size, and water holding capacity, water throughflow) relate to differences in food web structure and resource productivities, with the smallest and shallow reservoir Golinga being the most productive on a per unit area basis.

1.4 Thesis outline

The dissertation is divided into seven chapters. **Chapter 1** gives a general introduction highlighting the status and the importance of reservoirs fisheries and providing the rationale for the study. **Chapters 2 to 6** have been structured in a form of peer-reviewed articles. These chapters are linked to the two main objectives of the thesis with **Chapters 4 and 5** covering *objective i* and **Chapters 2, 3 and 6** focusing on the *objective ii*. The **7th chapter** discusses the key results from the preceding chapters with further elaboration on the study's conclusions and recommendations.

C**hapter one** sets the background for the study and places the study in the context of broader inland/small-scale fisheries. It also provides the rationale, objectives and hypotheses of the study. C**hapter 2** (*Manuscript 1,* entitled "*West African reservoirs and their fisheries: an assessment of harvest potential*", is published in *Ecohydrology & Hydrobiology)* focuses on assessing models for reservoirs harvest estimation using both primary (i.e. three focus reservoirs of the thesis) and secondary data (27 West African reservoirs). C**hapter 3** (*Manuscript 2,* entitled "*Elucidating differences in environmental variables: implications for reservoirs fisheries management in northern Ghana*", is *in preparation*) evaluates the physicochemical characteristics of the reservoirs and its implications for reservoirs fisheries management. C**hapter 4 (***Manuscript 3*, entitled "*Assessing the exploitation status of fisheries resources in Ghana's reservoirs based on reconstructed catches and length-based bootstrapping stock assessment method*" is published in *Lake and Reservoir Management*) provides a holistic assessment of the reservoirs' cichlid fishery (*Oreochromis niloticus*, *Sarotherondon galilaeus* and *Coptodon zillii*), using a robust approach in estimating growth, and mortality parameters, stock size, biological reference points and length-based indicators. C**hapter 5** (*Manuscript 4*, entitled **"***Comparing feeding niche, growth characteristics and exploitation level of the Giraffe catfish Auchenoglanis occidentalis (Valenciennes, 1775) in the two largest man-made lakes of northern Ghana*" is published in *African Journal of Aquatic Science*) focuses on aspects of the bio-ecology (knowledge of the feeding behaviour and exploitation status) of the Giraffe catfish (*Auchenoglanis occidentalis*) populations in lakes Bontanga and Tono. In **Chapter 6** (*Manuscript 5,* entitled "*Comparative assessment of biodiversity, food web structure and fisheries productivity of three man-made lakes in Ghana*", is submitted to *Freshwater Biology*), a comparative analysis of biodiversity, food web structures, and fisheries productivities of the reservoirs is presented and discussed in the context of ecosystem development, resilience and maturity and the **Chapter 7** discusses the main findings of the study with emphasis on the reservoirs resource status, potentials, assessment needs and implications for sustainable management.

CHAPTER 2: Assessment of reservoir harvest potential

West African reservoirs and their fisheries: An assessment of harvest potential

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Abstract

A major constraint to science-based fish stock management in West Africa is the lack of reliable data on target stocks. This especially holds true for inland fisheries, such as those that operate in reservoirs. Due to the low availability of resources and population data, and the limited number of fisheries experts in the region, state institutions and investigators rely heavily on simple catch statistics and empirical models for their estimations of fish production and potential yields. This paper reviews data from the FAO, and published articles and reports on West African reservoirs, with special reference to their morphometric and environmental features in relation to fish catch. In addition, we analyse primary data on three focus reservoirs. First, to improve and update available models of potential harvests from reservoirs, we regress fish catch data against reservoir surface area data for 30 reservoirs in West Africa, yielding the following equation: Catch (tonnes/year) = 17.3×Area (km^2)$^{0.8626}$. The equation accounts for 95.7% of the variation observed in the fish catches. Analysis of covariance of small (<2 km^2) and large (>2 km^2) reservoirs shows no significant difference (F=0.5895, p=0.45) in the slopes of the two groups. Second, we apply multiple regressions to a sub dataset of 15 reservoirs with surface area and mean depth as predictors; and we also explore reservoir age as a further variable. We find that fisheries productivity is inversely correlated with both mean depth (r=-0.49) and surface area (r=-0.32), but there is no significant correlation found with reservoir age (r=0.03).

Keywords: West Africa, reservoir, harvest potential, fish catch, surface area, regression.

2.1 Introduction

In developing countries, more than 60 million people rely on freshwater fisheries for their livelihood. Seventy-one low-income countries currently produce nearly seven million tonnes of fish a year, representing 80% of global inland fisheries capture (FAO, 2015). In West Africa, freshwater fish production is highly important to the food security of human populations (Pauly, 2017) with reservoirs, lakes and rivers throughout the region being important sources of protein and micronutrients. This sub-region has an average per capita fish consumption of 12.1 kg/year. Notwithstanding the importance of this industry, limited research has been focused on the reservoir fisheries in Western Africa. The FAO data on fish catch and fish supply in the region suggest that all fish capture from inland waters is being used for consumption within the region (Figure 2.1), and Kolding et al. (2016) highlight the importance of fisheries and aquaculture to the livelihoods of drylands communities of sub-Saharan Africa. However, despite the fact that it has been widely reported there are several thousand reservoirs (Kolding et al., 2016; Marshall and Maes, 1994; Venot et al., 2012) in sub-Saharan Africa, no accurate estimates of the number exist, nor their potential contribution to total inland fisheries capture.

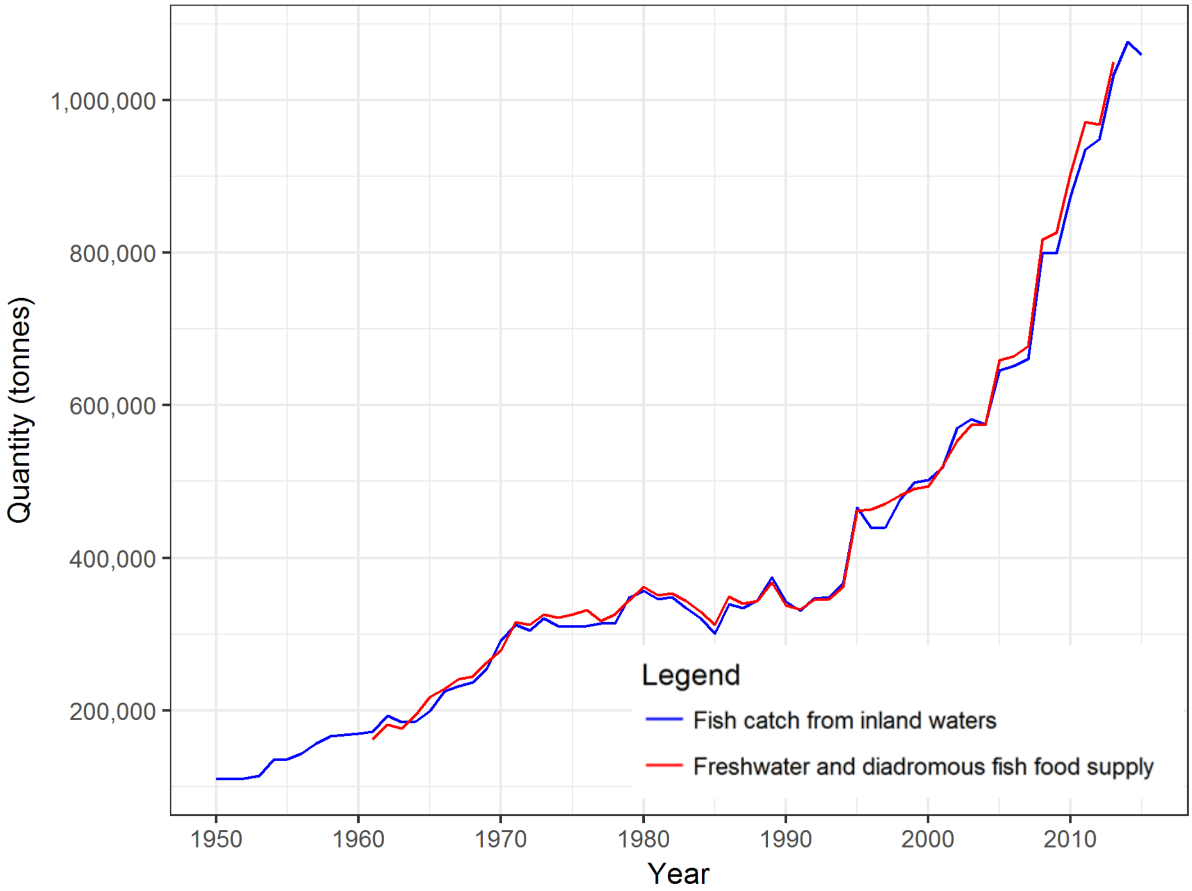

Figure 2.1. Fish catch from inland waters and freshwater and diadromous fish food supply in Western Africa. Data Source: (FAO, 2017).

Statistical models (mostly linear regressions) relating morphometric and edaphic factors to fish yields in temperate lakes and reservoirs were developed in the 1950s and 1960s. These showed that fish production in Canadian lakes was related to mean depth (Rawson, 1952), to water chemistry (Moyle, 1956) and to physical and chemical indices (Northcote and Larkin, 1956). Ryder (1965) combined these indices into a "morpho-edaphic index (MEI)" (defined as the total dissolved solids divided by the mean depth), for which he used 23 temperate lakes.

In tropical fresh water fisheries, the first application of Ryder's MEI was that of Henderson and Welcomme (1974), who applied it to a selected number of African inland waters. The MEI was related to yields from African tropical lakes and reservoirs, and from the Lake Bangweulu System (Toews and Griffith, 1979). In a further development of the model, a review on MEI was made by Schlesinger and Regier (1982) and, subsequently, fish yields from reservoirs were related to MEI by Bernacsek and Lopes (1984), and Marshall (1984). Youngs and Heimbuch (1982) were able to show that the surface area of a lake alone, is a very powerful predictor of catch. Marshall (1984) applied their model: $\log_e$ (Yield, in tonnes per year tyr^{-1})= $7.01 + 0.83 \log_e$ (Area, km^2), for the first time, to 17 African lakes and reservoirs. Later, Crul (1992) used a data set of 25 reservoirs, with catch data spanning from 1954-1984, to update this work and derived the following model: Catch (tyr^{-1}) = 7.09 $Area^{0.94}$ ($r^2 = 0.94$). Ideally, these models should be updated periodically to accommodate new information as it becomes available. For example, studies by Bhukaswan (1980); Gubiani et al. (2011) showed that the catch obtained from a water body may depend largely on the developmental state of the fishery; a significant finding, such as this, should be reflected in the models. However, due to limited catch data and limited resources, many of the models currently in use are old and in need of updating (Welcomme, 2011). Youngs and Heimbuch (1982), Marshall (1984) and Crul (1992) have all shown that, of all the factors analysed, surface area is the most powerful predictor of total catch in African reservoirs. Other factors such as primary production (Melack, 1976; Oglesby, 1977), water level fluctuations and discharge (FAO, 2016a; Kolding and van Zwieten, 2011) and total phosphorus levels (Hanson and Leggett, 1982), could also be useful predictors of fish yield but, unfortunately, information on these factors is only available for a very limited number of African inland waters. In this paper, we make an inventory of reservoirs in the region and analyse their potential harvest. In developing our model, we consider the following two observations:

(i) The current, observed total catch of reservoirs is not adequately predicted by the Crul (1992) model, since 28 of the West African sub-region reservoirs have catches that exceed the yields predicted by Crul’s model by an average of 50% (Annex I, Table S2.1).

(ii) Crul´s model was developed using datasets from a broad region (Africa). Considering the potential geographic differences in resource productivities (highlighted by Marten and Polovina (1982); Welcomme and Bartley (1998); Yamada and Ruttan (1980)), our model, in contrast to Crul’s, is limited to datasets from Western Africa only.

Reservoirs are man-made impoundments created mostly as a result of dam construction on rivers. They are used for community purposes including drinking water supply (e.g. Weija, and Barekese, Ghana), irrigation farming (e.g. Tono, Ghana; Bagré, Burkina Faso), and hydroelectric power generation (e.g. Kainji, Nigeria; Manantali and Sélingué, Mali). These waterbodies vary greatly in their surface areas and in other morphometric features such as their mean depth, water holding capacity and discharge. In most West African countries, fisheries normally develop as an incidental benefit or an intended livelihood as a result of reservoir construction. Considering the stagnating trend in marine capture fisheries production in the region, the potential contribution of reservoirs, and other inland water bodies, to capture fisheries production in the region should be explored to provide essential information for national fisheries management strategies. Additionally, the question of how morphometric characteristics of reservoirs, in the semi-arid region of West Africa, relate to fisheries productivity needs to be understood.

The tilapiine species (*S. galilaeus* and *O. niloticus*) of the family Cichlidae are the main fisheries resources in most African lakes and reservoirs (FAO, 2003). We present here, known data from a selection of the reservoirs. At Asejire reservoir, Nigeria, 19 fish species from 16 genera and 13 families were recorded during experimental gill nets fishing; the family Cichlidae were the most dominant, among which *Tilapia marie* was the most common species (Ipinmoroti et al., 2017). In Ghana, targeted cichlid species represented 89%, 74%, and 71% of the total catch composition (landed weight) at Tono, Bontanga, and Golinga reservoirs, respectively (Abobi et al., 2019a). In Côte d'Ivoire, the catch composition of Taboo reservoir showed predominance of *Chrysichthys spp.* (58.4%) and tilapiine fish (35.8%). Other fish species such as *Clarias spp.* (2.5 %), Mormyrids (1%), *Heterotis niloticus* (0.8%) and *Schilbe spp.* (0.7%) were represented (Aliko et al., 2014). In the Reservoir Ayamé, Côte d'Ivoire, the most abundant families were Alestidae (36.61%), Cichlidae (34.19%), and Claroteidae (13.43%) (Mamadou et al., 2019) and in Reservoir Buyo, Côte d'Ivoire, the fish biomass was dominated by Cichlidae (32.27%) and Claroteidae (26.35%). In Mali, the top five most frequently encountered species at: i) Reservoir Manantali were *Lates niloticus* (74.6%), *Sarotherodon galilaeus* (65.7%), *Oreochromis aureus* (61.2%), *Synodontis schall* (43.1%), and *Synodontis ocellifer* (40.8%); and ii) Reservoir Selengue were *Chrysichthys nigrodigitatus* (34.6%), *Auchenoglanis occidentalis* (34.1%), *Sarotherodon galilaeus* (32%), *Labeo senegalensis* (29.4%), and *Synodontis membranaceus* (26.4%) (Laë et al., 2004).

The main objective of this contribution is, thus, to review the sparse information on total fish catch of West African reservoirs and derive an updated, predictive model for fisheries production from the reservoirs. Following the reasoning of Oglesby (1977) and Petrere (1996), on the relationship between lake size and fish yields, the paper explores the potential differences in productivity between small and large reservoirs, and considers further potential predictors for the fish catch (such as mean reservoir depth and age).

2.2 Materials and methods

2.2.1 Geographic and climatic characteristics of West Africa

West Africa covers an area of approximately 6 million km^2, which is about 20% of Africa’s total land area. The region lies between longitudes 18°W and 16°E, and latitudes 3° and 28°N, and it is bounded in the west and south by the Atlantic Ocean, in the north by the Sahara desert, and in the east by the Central African nations of Chad and Cameroon. The topography of the region is mainly flat (with most parts lying less than 300 m above mean sea level), although there exist several isolated high points in the coastal areas (Andam-Akorful et al., 2017).

The climate of Western Africa can be described predominantly as that of a dryland encompassing arid, semi-arid and dry sub-humid regions, corresponding to aridity index values of 0.05–0.20, 0.20–0.50 and 0.50–0.65 respectively. The region is conventionally classified into three sub-climatic zones namely: i) the dry north, known as the Sahel, which lies just below the Sahara desert; ii) the Sudano transitional zone; and iii) the relatively wet Guinean zone located in the south (Meynadier et al., 2010). The geographic distribution of wet and dry regions depends on the latitude and the distance from the Atlantic Ocean while the degree of aridity increases from south to north and to a lesser extent from west to east, as reported by Menz (2010). Temperatures in the lowlands of West Africa are high throughout the year, with annual means usually above 18°C. In the Sahel, maximum temperatures can reach above 40°C (for further details on the region's climate see CILSS, 2016).

2.2.2 Data sources, use and collection

Data sources

For this review, two FAO databases were used: i) FishstatJ provided data for the analysis of West African inland fisheries production and consumption; and ii) Aquastat provided data on the reservoirs' physical features. In addition, published articles and reports containing information on specific reservoir's physical features, fisheries production and catch statistics were used (Table 2.1). The Aquastat data were checked for consistency by comparing them with published literature.

Data use and collection

First, data from the Aquastat database (FAO, 2016b), and other sources (Annex I, Tables S2.2 and S2.3), were used to estimate the number of reservoirs and their total surface area in West Africa.

Second, data on water level fluctuations, surface area fluctuations and fish catches from three reservoirs in Ghana (namely Tono, Bontanga and Golinga) were obtained from July 2016 to June 2017 through field data collection. The water level was recorded monthly from fixed graduated poles at the three reservoirs. Using a Garmin GPS, the area of the three reservoirs was measured in August 2016 (peak of flood season) and in April 2017 (peak of dry season). Total fish landings were recorded for five consecutive days staring from Monday to Friday at Tono, and from Tuesday to Saturday at Bontanga and Golinga in each month and extrapolated to the monthly catch using an estimate of the average number of fishing days per month. Respective information was obtained from the fishers at the three reservoirs.

2.2.3 Catch, surface area, age and mean depth data from selected West African reservoirs

From seven West African countries, 30 small to large reservoirs were analysed for correlation between catch and surface area (Figure 2.2 and Table 2.1). All the reservoirs were included in a single-predictor regression. Then, for a subset of 15 reservoirs that had additional information on age and mean depth, a multiple regression analysis was conducted.

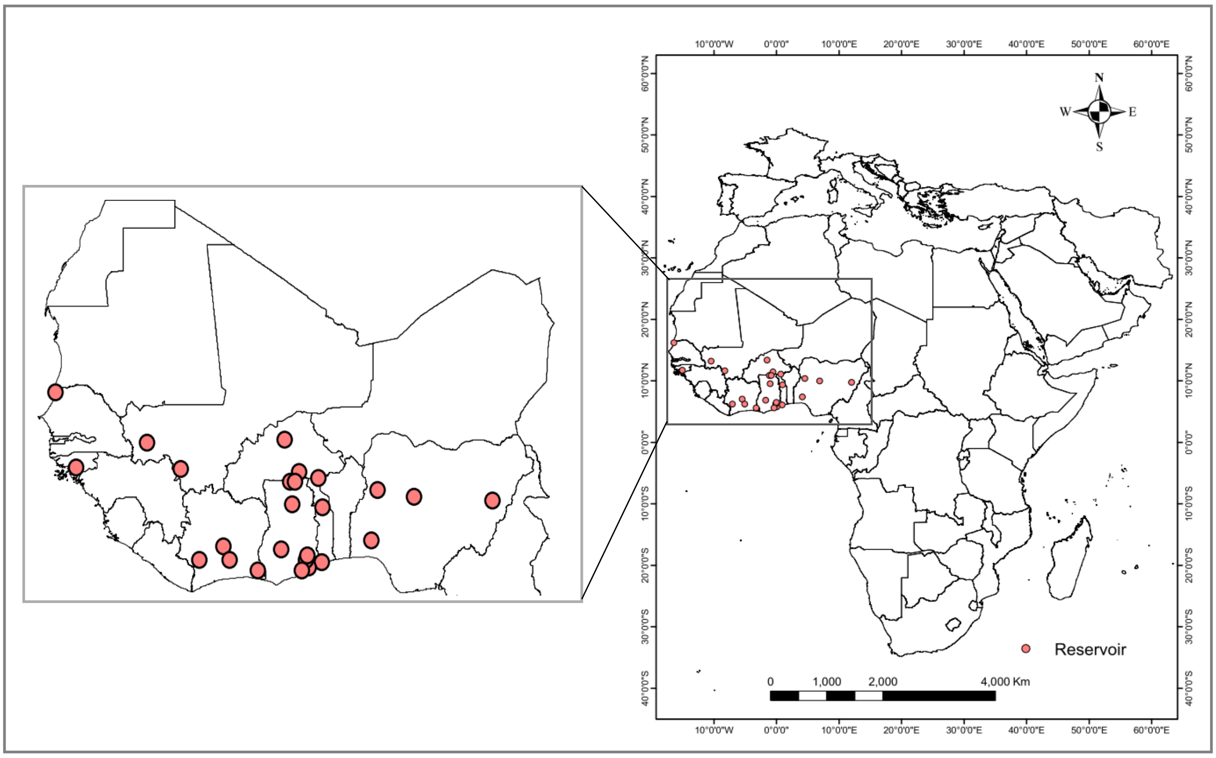

Figure 2.2. Map of Africa: the dots show the locations of 30 reservoirs analysed in the model.

Table 2.1. Morphometric and catch data of the 30 reservoirs. MR* indicates the 15 reservoirs used in the multiple regression analysis.

≠ [MR *]	Country	Reservoir name	Location	Surface area [km^2]	Mean depth [m]	Age [in 2018]	Total annual catch [tons/yr]	Year of catch report	Yield [kg/ha/ yr]	Source [Area; Catch; Mean depth]
1MR	Burkina Faso	Bagré	11°28′36.78″N 0°32′48.10″W	150	20	24	1040	2004	69.3	(Vanden Bossche and Bernacsek, 1990b); (Béné, 2007) (Villanueva et al., 2006)
2 MR	Burkina Faso	Kompienga	11° 4′ 55.56″ N 0° 41′ 59.28″ E	150	11.68	30	1243	1997	82.9	(Vanden Bossche and Bernacsek, 1990b); (Béné, 2007) (Ouédraogo et al., 2015) (Cecchi et al., 2008)
3 MR	Côte d'Ivoire	Ayamé	05°35′59.99″N 03°13′22.54″W	180	10	67	1061	1996	58.9	(Traore et al., 2008); (Traore et al., 2008); (Laë, 1997); (Duponchelle and Legendre, 2000)
4	Côte d'Ivoire	Buyo	06°14′32″N 07°02′05″W	900		38	4345	1992	48.3	(Van der Knaap, 1994); (Van der Knaap, 1994) (Lévêque, 1999)
5	Côte d'Ivoire	Gboyo		0.07			4.442	1999	634.6	(Gourdin, 1999); (de Morais, 2001)
6	Côte d'Ivoire	Katiali		0.24			4.082	1999	170.1	(Gourdin, 1999); (de Morais, 2001)
7	Côte d'Ivoire	Korokara T		0.07			1.925	1999	275	(Gourdin, 1999); (de Morais, 2001)
8 MR	Côte d'Ivoire	Kossou	7°1′52.57″N 5°28′23.16″W	900	10	47	7000	2000	77.8	(Lévêque, 1999); (Lévêque, 1999)
9	Côte d'Ivoire	Nambingué	8" to 10" N, 5" to 6" W	0.1			1.825	1999	182.5	(Gourdin, 1999); (de Morais, 2001)
10	Côte d'Ivoire	Sambakaha		0.15			7.572	1999	504.8	(Gourdin, 1999); (de Morais, 2001)
11	Côte d'Ivoire	Taboo	06°12′38″N 05°05′02″W	34.6		40	70.67	2006	20.4	(Aliko et al., 2014); (Aliko et al., 2014)
12	Côte d'Ivoire	Tiaplé		0.07			1.069	1999	152.7	(Gourdin, 1999); (de Morais, 2001)
13	Côte d'Ivoire	Tiné	8" to 10" N, 5" to 6" W	0.45			5.811	1999	129.1	(Gourdin, 1999); (de Morais, 2001)
14	Ghana	Afife	6° 04′ N, 0° 55′ E	5.5		56	70	1988	127.3	(Vanden Bossche and Bernacsek, 1990b); (Vanden Bossche and Bernacsek, 1990b) GIDA
15 MR	Ghana	Barekese	6°50'22.34″ N 1° 42' 55.62″W	6.4	6.4	48	80	1988	125	(Vanden Bossche and Bernacsek, 1990b); (Vanden Bossche and Bernacsek, 1990b); (Amuzu, 1975; Tetteh et al., 2006)
16 MR	Ghana	Bontanga	9° 33′ 2.88″ N 1° 01′ 7.68″ W	6.7	5.9	32	105.82	2017	158	This study; (Quarcoopome et al., 2008)

17 MR	Ghana	Dawhenya	5°46'58.09″ N 0° 03' 05.62″E	2.2	5.4	43	30	1988	136.4	(Vanden Bossche and Bernacsek, 1990b); (Vanden Bossche and Bernacsek, 1990b); (Alhassan, 2011);(Sam-Amoah and Gowing, 2001)
18 MR	Ghana	Golinga	9° 21′ 48.96″ N 0° 57′ 18″ W	0.62	2.7	44	10.66	2017	172	This study; (Gordon, 2006)
19 MR	Ghana	Kpong	6° 13′ 51″ N 0° 5′ 29″ W	25.2	5	37	186.68	2013	74.1	(FAO, 2016b); (Nunoo and Asiedu, 2013); (Quarcoopome et al., 2011)
20 MR	Ghana	Tono	10° 53′ 6″ N 1° 09′ 18″ W	18.6	6.8	43	187.20	2017	101	(FAO, 2016b); This study; (Vanden Bossche and Bernacsek, 1990b)
21	Ghana	Vea	10° 52′ 30″ N 0° 50′ 42″ W	4.05		53	33.5	2010	82.7	(Adongo et al., 2014); (Okrah, 2010); (Vanden Bossche and Bernacsek, 1990b)
22 MR	Ghana	Weija	5°35'10.82″ N 0° 21' 16.62″W	37	5	41	420	1988	113.5	(Vanden Bossche and Bernacsek, 1990b); (Vanden Bossche and Bernacsek, 1990b) (Asante et al., 2008)
23 MR	Mail	Manantali	13°11′44″N 10°25′44″W	500	21	31	1500	1999	30	(Lévêque, 1999); (Lévêque, 1999); (Kantoussan et al., 2009)
24 MR	Mail	Selingue	11°38′17.7″N 8°13′47.2″W	400	5	38	4000	1999	100	(Lévêque, 1999); (Lévêque, 1999);(Kantoussan et al., 2009)
25	Nigeria	Asejire	7°21′45″N 4°08′00″E	23.69		29	1029	1985	434.4	(Ita et al., 1985); (Ita, 1993); (FAO, 2016b)
26	Nigeria	IITA		0.78		49	13.8	1986	176.9	(FAO, 2016b); (Ita, 1993); (Peacock, 2010)
27 MR	Nigeria	Kainji lake	10°22′N 4°33′E	1270	11	50	13361	2001	105.2	(Vanden Bossche and Bernacsek, 1990b); (Fernando and Holčík, 1982);(Abiodun, 2002)
28	Nigeria	Kiri	9°44'59"N 12°1'0"E	115		36	2473	1985	215	(Ita et al., 1985); (Ita, 1993); (FAO, 2016b)
29 MR	Nigeria	Shiroro	9°59'7"N 6°54'58"E	312	36	29	3489	1990	111.8	(FAO, 2016b); (Ita, 1993); (Ovie and Adeniji, 1994)
30	Senegal	Diama	16°13′0.20″N 16°24′53.63″W	235		32	4500.0	2003	191.5	(FAO, 2016b); (Degeorges and Reilly, 2006)

2.2.4 **Modelling approaches used**

Approach 1: Simple catch-area regression

A simple catch-area regression was first constructed for all 30 reservoirs with double-logarithmic transformation (1):

$$ln(\text{Catch}) = \text{a} + \text{b}.\,ln(\text{Area}) \qquad (1)$$

Where fish catch is in tonnes per year and reservoir area is in square kilometres. The resulting single regression line was then tested for an inflection point using a technique described by Somerton (1980) to check if small and large reservoirs differed in terms of their catch-area relationship. The data were repeatedly divided into two groups and regressions were calculated for each group. The residual sum of squares of both lines was then summed and the calculation was repeated with another pair of regression lines until the residual sum of squares approached a minimum. An inflection point exists if the pooled residual sum of squares of a pair of the resulting regression lines is significantly lower than the residual sum of squares of a single line. The dataset was then fitted using the dummy variable regression (DVR) method, which is an analysis of covariance (ANCOVA) for comparison of two regression lines (Fox, 1997). Our DVR model consisted of ln (Area) as a quantitative explanatory variable or the covariate, size (i.e. the reservoir group with two levels: A, above 2 km^2; and B, below 2 km^2) as the dummy variable or factor and the interaction between the dummy variable and the covariate. The resulting equation was:

$$ln(\text{Catch}) = ln(\text{Area}) + \text{Size} + \text{Size}{:}\,ln(\text{Area}) \qquad (2)$$

Approach 2: Multiple linear regressions

Using a subset of the data (15 reservoirs that had information available on both age and mean depth), multiple linear regression relationships were fitted to test for the effect of the two additional variables (i.e. age and mean depth) in explaining the catch variations of the datasets. A three-way combination of the main effects led to an increase of variance due to the small sample size. The multiple regression relationships were preceded by a simple catch-area regression fitted for the 15 reservoirs, followed by multiple regression using both mean depth in meters (3) and reservoir age in years (4).

a) $ln(\text{Catch}) = \text{a} + \text{b}.\,ln(\text{Area}) \times ln(\text{mean depth})$ (3)

b) $ln(\text{Catch}) = \text{a} + \text{b}.\,ln(\text{Area}) \times ln(\text{Age})$ (4)

As it is widely known that using allometric equations to predict unknown values of y produces a logarithmic transformation bias (Smith, 1993), the predicted fish yield values in log scale were back-transformed with a correction factor (5) for natural logarithms provided by (Sprugel, 1983) as:

$$\mathrm{CF} = \exp\left((SEE^2)/2\right) \tag{5}$$

The term SEE is the (residual) standard error estimate of the regression equation.

The models were checked to see if the errors were independent, normally distributed in each group, and had a constant variance in each group (homoscedastic). These assumptions were assessed by interpreting the residual plot and the histogram of residuals. Then, residuals of the models were tested to see if they were normally distributed using both the Anderson-Darling and Cramer-von Mises normality tests. Both tests revealed no evidence against normality (p=0.08 and p=0.08 for Model 1, and p= 0.60 and p=0.58 for Model 2, for the Anderson-Darling and Cramer-von Mises normality tests, respectively). The assumptions of linear models were adequately met for the data (Annex I, Figures S2.1 and S2.2). All data analyses were conducted using R 3.5.0 software (R Core, 2018).

2.3 Results

2.3.1 Assessment of the number of reservoirs in western Africa and their overall surface

We estimate that there are about 6,894 reservoirs in West Africa with combined surface area of 27,504 km^2 (See Annex I, Table S2.3). Most of them have been reported as small reservoirs with surface areas within the range of 1-1,000 ha (≤10km^2). Burkina Faso appears to be the country with the highest number of small reservoirs (Figure 2.3, Annex I, Table S2.1). The two largest reservoirs in the sub-region with surface areas above 1,000 km^2 at upper storage level, are the Volta (8,482 km^2) and Kainji lakes (1,270 km^2). However, the FAO Aquastat database is not exhaustive. It has only 420 reservoirs registered in the sub-region and it has no records of small reservoirs with surface area below 10 ha (<0.1 km^2).

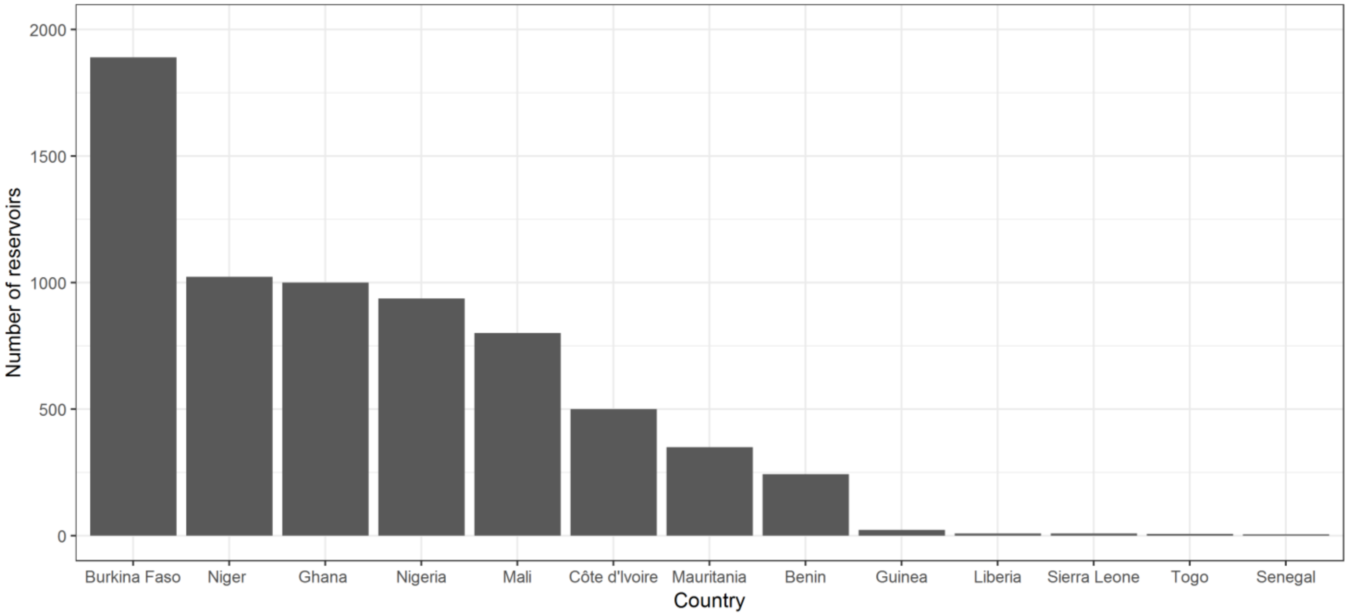

Figure 2.3. Number of reservoirs by country in West Africa. For exact values and sources of data consider Table S2.2 of Annex I.

The three focus reservoirs of Northern Ghana used in this study (namely Tono, Bontanga and Golinga) were seen to have significant intra annual change in their surface area and water levels (Table 2.2); the smallest reservoir (Golinga) lost more than 50% of its surface area during the dry season. Monthly water levels of the reservoirs were inversely correlated with total catches, with correlation coefficient (r) giving values of -0.70, -0.93 and -0.56 for Tono, Bontanga and Golinga reservoirs, respectively (Annex I, Figure S2.3).

Table 2.2. Seasonal fluctuation in surface area and water level of Tono, Bontanga and Golinga reservoirs of Ghana from July 2016 to June 2017; measurements taken in the flood season (August 2016) and the dry season (April 2017). For monthly variation in fish catch and water level in the reservoirs, see Annex I, Figure S2.3.

Parameter	Tono	Bontanga	Golinga
Surface area during flood season (km^2)	18.6	6.7	0.62
Surface area during dry season (km^2)	12.5	3.8	0.3
Seasonal reduction in surface area (%)	32.8	43.3	51.6
Mean depth (m)	6.6	5.9	2.7
Maximum depth (m)	13.32	9.7	4.95
Water level variation (m)	5.46	5.38	2.68
Water level: Flood-Dry (m)	10.5-5.04	8.23-2.85	2.8-0.12
*Relative Reservoir Level Fluctuation	82.7	91.2	99.6

Adapted from (Jul-Larsen et al., 2003): mean reservoir level amplitude/mean depth 100

2.3.2 Catch-area relationship of West African reservoirs

Using segmented regression, as applied by Somerton (1980), we found an inflection in reservoir size at 2 km^2. However, analysis of covariance showed that the resulting two groups (A and B for reservoirs with surface areas above and below 2 km^2, respectively; see Annex I, Figure S2.4) had no significant difference in their slopes, with F= 0.5895, d.f. =26, 3, and p=0.45, (for more detail see Annex I, Figure S2.5). Thus, the catch-area relationship was modelled with a single equation for all the reservoirs. The resulting model was:

Model 1: Catch (tonnes/year), Area (km^2)

$$\text{Catch} = 17.3(95\%\text{CI: } 13 - 23) \times \text{Area}^{0.8626\ (95\%\text{CI: } 0.7915-0.9336)}$$

n=30, r^2=0.957, p=1.3e-20, Mean Squared Error= 0.3402

The correction factor for adjusting the back-transformation of the predicted yields to the original scale (fish catch in tonnes per year) is 1.1999. The fit to the catch-area dataset explains 95.7% of the variation of observed catches. The expected fish catch of a reservoir with a known area can be observed from Figure 2.4.

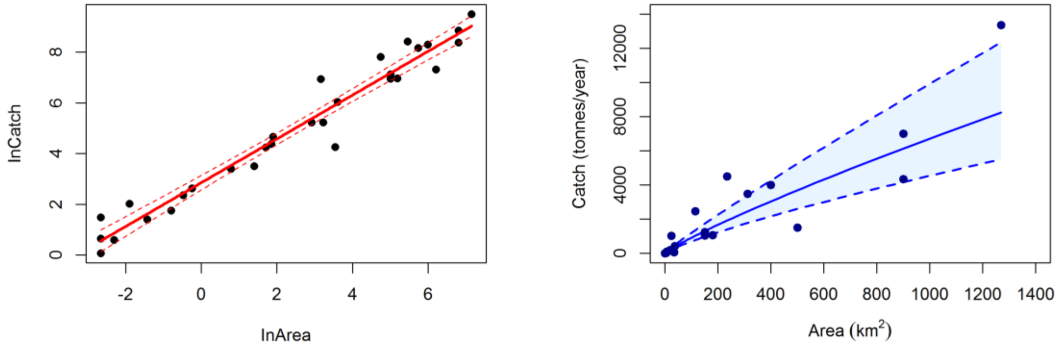

Figure 2.4. The ln- transformed (left) and back-transformed (right) catch-area data with the best-fit line (solid) superimposed and 95% confidence zone shown (within dotted lines).

2.3.3 Fish productivity and yield predictions

Using a range of reservoir surface area values, we compared the fish productivity predicted (tonnes/km^2/year) by the model of this study to that of Crul's model. The model of this study predicted, on average, more than twice what Crul's model predicts (Figure 2.5; Annex I, Table S2.4). A t-test on the data showed that the mean of the productivity estimates (of Crul's 6.2 tonnes/km^2/year and this study's 16.3 tonnes/km^2/year: see Annex I, Table S2.4) are significantly different ($t = -5.7252$, $df = 38$, p-value=0.00000136; see Annex I, Figure S2.6). Analysis of the sub-dataset (i.e. the 15 reservoirs where additional information was available) showed that the fish productivity per unit area of the reservoirs was inversely correlated both with mean depth ($r=-0.49$) and area ($r=-0.32$), but not with age ($r=0.03$) (Figure 2.6).

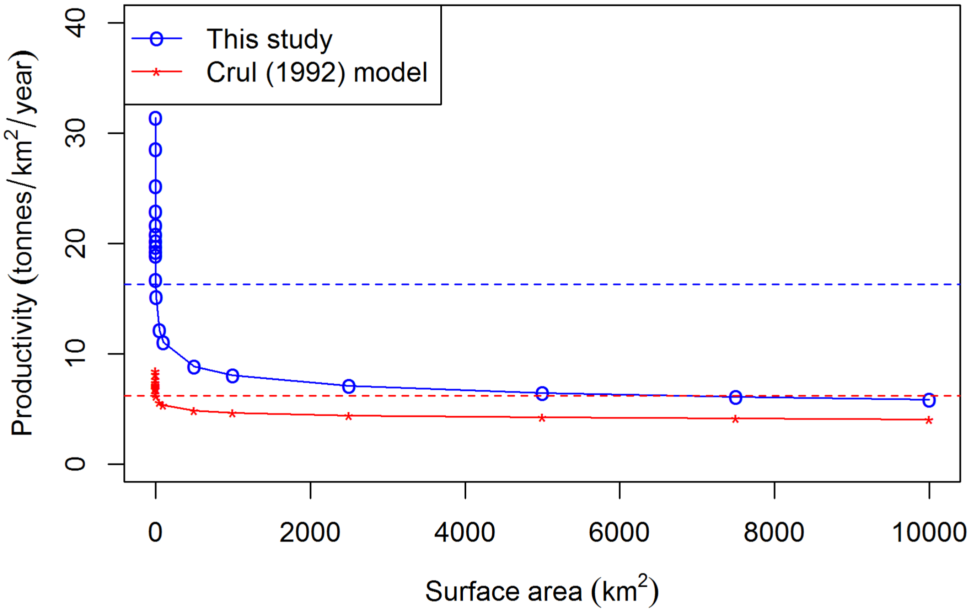

Figure 2.5. Comparison of productivity estimate from this study and from Crul's model (1992). The dotted lines represent the means of the estimates.

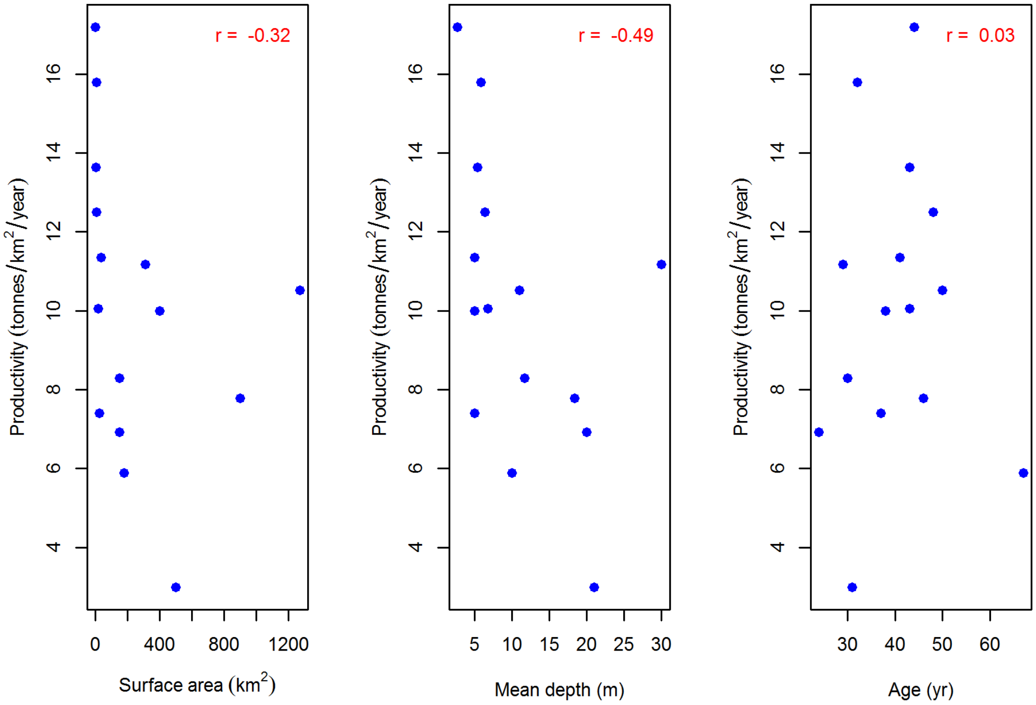

Figure 2.6. Correlation between productivity and surface area (km^2), mean depth (m) and age (yr) of 15 reservoirs.

2.3.4 Multiple regression with area, age and mean depth data of 15 reservoirs

While a multiple linear regression of catch against area (km^2), age (year) and mean depth (m) of the 15 reservoirs did not produce a reliable model, catch regressed against area and mean depth produced a predictive model (hereafter referred to as Model 2) that explained 87% of the variation in fish catch.

Model 2: Catch (tonnes/year), Area (km^2), mean depth (m)

$$\text{lnCatch} = 3.5 + 0.015\text{Area} + 0.15\text{Depth} - (0.00005 \times \text{Area}^2) - (0.00044\text{Area} \times \text{Depth})$$

n=15, r^2=0.8738, p=0.000172, Mean Squared Error = 0.4994

Table 2.3. Confidence limits of the parameters of Model 2 (i.e. multiple linear regression). Details on residuals and summary statistics of the model are available in Annex I, Figure S2.4.

Parameter	Coefficient	Lower limit	Upper limit
(Intercept)	3.5005850	2.3507990	4.6503710
Area	0.0148636	0.0073007	0.0224264
Depth	0.1490164	0.0168920	0.2811408
I(Area^2)	-0.0000051	-0.0000099	-0.0000003
Area: depth	-0.0004363	-0.0008053	-0.0000673

2.4 Discussion

2.4.1 Assessment of reservoirs in West Africa

It has been widely reported that there are several thousand reservoirs in sub-Saharan Africa (Kolding et al., 2016; Marshall and Maes, 1994; Venot et al., 2012). Our study estimated a total of 6,894 reservoirs covering approximately 27,504 km^2 of area in the West African sub region. We estimated that the reservoirs of the region combined contribute 116,806.3 tonnes (95% CI: 42,435.1-320,883.8 tonnes) per annum to the inland capture fisheries of the region, which represented 12.4% of the region's total inland fish catch (940,767 tonnes/annum on average) as reported by the FAO (2008-2015). Our results were comparable to estimates by Petr (1994) who reported that, in Africa, reservoir fisheries contribute about 15,000 tonnes (10%) to the overall inland fishery of the continent. Our model, and that of Crul (1992), were both developed with datasets of man-made lakes only and, are thus, comparable.

2.4.2 Models and harvest potential estimate

In our study we followed the modelling approach of Youngs and Heimbuch (1982), which regresses the logarithm of fish catch against the logarithm of reservoir surface area. Our model accounts for 95.7% of the observed variation in catches of the reservoirs. However, our potential yield estimates greatly exceed those of the model by Crul (1992). This difference may be explained by multiple factors. We believe that the higher current catches of the reservoirs in the region are in part, due to restocking activities that were accelerated mainly in the 1990s (Ouedraogo, 2010). Population growth has contributed to an increase in fishing pressure and, together with gear diversification and the optimization of fishing techniques, may have driven total harvest levels to increase. Petr (1994) observed that fish production in Africa kept pace with the rise in human population and reported that, over a period of 17 years, the human population increase of 79% corresponded to a 74% increase in fish production. So, it is reasonable to assume that the difference in the estimates between the model of this study, in 2018, and the previous model of Crul (1992) can be attributed to the above factors. Furthermore, increases in the productivity of reservoirs are also related to eutrophication. Nixon (1995) defined eutrophication as 'an increase in the rate of supply of organic matter to an ecosystem'. Eutrophication tends to affect shallow lake systems more than deeper tropical lakes (Kemka et al., 2006). Population growth, intensified agriculture (including the use of agrochemicals) and deforestation are the main drivers of nutrient-rich inflows into shallow tropical reservoirs (Ndebele-Murisa et al., 2010; Ntiba et al., 2001).

Our study shows that productivity per unit area greatly decreases as the size of the reservoir increases; a reservoir with surface area of 1 km^2 is twice more productive (per unit area) than a 100 km^2 reservoir. These results corroborate findings by Fernando and Holčík (1982) that small and shallow African lakes are more productive than larger ones. Most small reservoirs are constructed mainly for community water storage and livestock watering. Animal wastes and dung deposition at the edges of the reservoirs are sources of both nitrogen and phosphorus (Ansari et al., 2010; Kolding et al., 2016). Consequently, small reservoirs are highly productive. Baijot et al. (1997) found that small reservoirs in Burkina Faso are richer in mineral concentrations than large artificial lakes, but are less stable. Our findings that there is a decline of fish productivity per unit area as both reservoir surface area and mean depth increase agrees with a study by Downing (2010), according to which, fish productivity generally declines with increasing lake size. Depth, water chemistry and conductivity have all been used to classify lakes and reservoirs (Rai and Hill, 1980; Talling and Talling, 1965), since these parameters appear to be closely related with productivity (Downing et al., 1990; Henderson and Welcomme, 1974; Ryder et al., 1974). Rawson (1938) was the first to suggest that factors affecting lake productivity could be grouped into climatic, morphometric, and edaphic factors. It has been shown that biological production in lake systems is partly controlled by lake morphology, nutrients and other environmental factors (Kolding and Van Zwieten, 2006; Kolding and van Zwieten, 2012; Figure 2.7a). Some of these studies suggest that fish productivity per unit area is negatively related with habitat volume, area, and mean depth since many aquatic processes are less intense, and fish is less abundant (per unit area) in larger water bodies. This is attributed to decreased rates of nutrient recycling to the euphotic layer within these lakes (Downing, 2010; Figure 2.7b and c). The tilapiine species, *O. niloticus* and *S. galilaeus*, which are the mainstays of most reservoir fisheries, are more productive in the relatively small Golinga than in the large Tono and Bontanga (Abobi et al., 2019a), due to the species' preferences for shallow waters (FAO, 2009a).

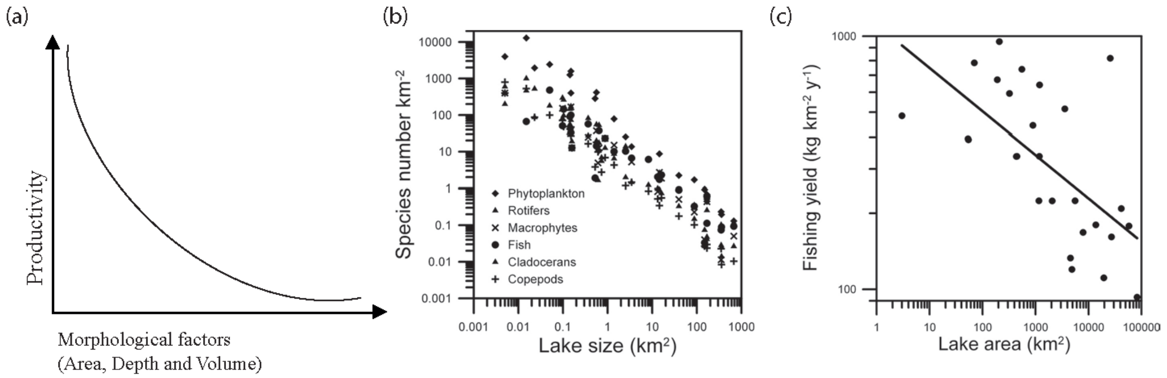

Figure 2.7. (a) Generalised morphological effects on the productivity of lakes and reservoirs, adapted from Kolding and Van Zwieten (2006); (b) Species-richness per unit area of various aquatic taxa in lakes of different sizes (after Downing, 2010); and (c) Fish yield and lake-size data summarised by Youngs and Heimbuch (1982) from other sources (Matuszek, 1978; Oglesby, 1977; Ryder, 1965) and adapted from Downing (2010).

Reservoirs serve multiple community needs and, in this light, their resources are often subjected to severe competition between irrigation farming and fisheries. Therefore, in estimating reservoir fisheries production, the effects of water drawdown caused by irrigation should be considered; as intensive use of reservoir waters for farming reduces the size of the aquatic habitat available to fish production. According to Jul-Larsen et al. (2003), Kolding and van Zwieten (2011), Kolding and van Zwieten (2012), Kolding et al. (2016) and Gownaris et al. (2017), however, there is increasing evidence that inland fish production in Africa is more dependent on external climatic drivers, such as seasonal variability of water levels, than on human exploitation rates or management interventions. The relation between seasonal variability of surface water bodies and fish production is consistent with our observations on the three reservoirs in northern Ghana, where the drawdown of water for irrigation during the dry seasons, rather than external climatic drivers, significantly reduces reservoir surface area and depth. Golinga reservoir, a small water body with a surface area at full storage of 0.62 km^2 experienced 52% and 2.68 m reduction in surface area and water level, respectively, mainly as a result of intensive withdrawal of water for irrigation during the dry season. Similar observations on small reservoirs in Burkina Faso have been made by Kolding et al. (2016). This phenomenon means that in years of high evaporation and little rainfall, these small reservoirs, while highly productive under “normal conditions”, may lose a large part (if not all) of their fish productivity if abstraction for irrigation continues. Kolding et al. (2016) asserts that the impact of water level fluctuations in African lakes and reservoirs is inversely proportional to the size and depth of the system, implying that trends in rainfall, evaporation and siltation will be crucial to the resilience and productivity of the over 6,000 small and shallow reservoirs in the region.

Intra annual variation in total fish catch of reservoirs is also influenced by seasonal changes in livelihood activities. For example, the lean farming season (dry season) may lead to a sudden boom in fishing activities at reservoirs where there is open access to the fishery. We observed a clear case of a livelihood-induced, seasonal fishing boom between March and April at Golinga reservoir in the Northern region of Ghana. The number of fishers on the reservoir tripled during these two months of lowest water levels. The open access allowed the occasional fishers without wooden canoes to practice ‘‘step in and cast’’ fishing. Therefore, the recorded monthly catches were highest in March and April. Bontanga and Tono, on the contrary, had the highest catches in May. We believe that fish are abundant in the reservoirs during the flood and post flood seasons

(July-December), but are mostly harvested when the water level draws down and fish are concentrated in the reservoir increasing their catchability.

Some studies have shown that seasonal fluctuations in water level are associated with enhanced productivity (Junk et al., 1989; Kolding, 1993; Wantzen et al., 2008). Moreover, fluctuations of the aquatic terrestrial transition zone (ATTZ) depend on seasonal water level fluctuations. Kolding et al. (2016) report on increased phosphorous mobilization following wet–dry cycles owing to the alteration of physical, microbial and chemical processes in the ATTZ. Among the three reservoirs of this study, Golinga, which is the smallest, had the highest intra annual fluctuation in surface area (52% reduction) but was the most productive with total catch of 17.2 tonnes/km^2/year. Golinga was followed by Bontanga, which had a 43% reduction in its surface area and fish productivity of 15.8 tonnes/km^2/year and, then, by Tono with a 33% reduction in its surface area and fish productivity of 10.1 tonnes/km^2/year. These results confirm a finding by Kolding et al. (2016), which states that the more the water level in the system fluctuates on a regular basis, the higher is the average productivity.

Youngs and Heimbuch (1982) demonstrated that 97% of the variation in a regression equation was explained by three factors: area, mean depth and total dissolved solids. While a multiple factor model should be applied whenever possible, in Western Africa, data to do this, presently, is unavailable.

In our second modelling approach (Model 2), we showed that depth was a significant predictor but that reservoir age was not. However, we think that this may be due to the low sample size (15) and narrow age difference (most are within 10 years in age) of the reservoirs used for the study. Following the observations by MRAG (1995) on the effect of sample size on multiple linear regression relationships for reservoirs and lakes fish yield, we think that a larger number of reservoirs, with a wider age range, would show a positive relation. This needs to be proven in a follow-up study.

Model 2 may be applied whenever the mean depth of the reservoir is known. However, considering the high coefficient of determination and the low prediction error, we recommend that Model 1 should be preferred until a larger sample size allows for revisiting (and possibly improving) Model 2. The difference of potential yield estimates between these two models largely depends on the interaction effect of area×depth of the individual reservoir being predicted by Model 2. The average difference was 57% for the sub data set analysed.

2.4.3 Model application, limitations and proxies

The models of this study are suitable for estimating fish catch from reservoirs of West Africa. As the fisheries of these reservoirs are mostly unrecorded and undocumented, their yield contribution to the total fisheries production of the region can be approximated by our models.

We can also think of applying our model equations during the reservoir planning process since the expected fish yield, as well as the potential water supply for other uses can be calculated for a reservoir of a specific area (and depth). This could be compared to expected reservoir construction costs, providing a sound base for cost benefit analysis. This reasoning has been successfully applied in the utilisation of small and medium-sized reservoirs in China, where fishery aspects were taken into account at the planning stage of reservoir construction (De Silva, 2000).

Annual changes in fish catches from lakes and reservoirs are common and the factors behind these changes can vary. Therefore, it would be desirable to constantly update the information and data from the water bodies to be considered for the model. We recommend either continuous biannual surveys, preferably during the peaks of the wet and dry seasons or a full year study every five years. Future data could comprise changes in the: number of fishers/boats, number of active fishing days, introduction/withdrawal of fishing gears/crafts and water volume. Similarly, the average annual water levels of large reservoirs, whose surface areas are monitored by satellites, can be obtained (for example, from the United States Department of Agriculture) and used as proxies for assessing annual variations in the reservoirs' sizes and fish catches.

Our two models, just like those of Youngs and Heimbuch (1982) and Crul (1992), are based on data of catch and surface area (and reservoir depth) and do not include fishing effort or other potentially influencing factors. Following the reasoning of FAO (2016a); Kolding and van Zwieten (2011, 2012); MRAG (1995), we suggest that further development of catch-area relationships into multiple regression models should be done with one or several of the following additional variables: Chlorophyll "a" (µg/l), number of fishers/number of boats, water level fluctuation (m), volume (m^3) and discharge (m^3/s). It would be useful to obtain depth data on more reservoirs for further progress on empirical models to predict fish yields of West African reservoirs.

CHAPTER 3: Physicochemical characteristics of Tono, Bontanga and Golinga reservoirs

Elucidating differences in environmental variables: implications for reservoirs fisheries management in northern Ghana

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Abstract

This study was conducted to identify the limnological patterns in Tono, Bontanga and Golinga reservoirs. Chlorophyll *a*, dissolved oxygen, temperature, turbidity, water transparency, electrical conductivity, pH and nutrients were analysed for seasonal variations using samples collected from July 2016 to June 2017. The results showed variations in physicochemical parameters between the four seasons of the region (i.e. wet, post-wet, dry and pre-wet) and also between the three studied reservoirs. The smallest shallow (Golinga) reservoir had significantly higher concentrations of DOC and TDNb than Tono and Bontanga reservoirs, while o-$SiO_4{}^{4-}$ content was significantly higher in the large deep (Tono) reservoir than Bontanga and Golinga reservoirs. The results indicated no significant difference in the concentrations of o-$PO_4{}^{3-}$, NO3-N and NH4-N between the reservoirs (o-$PO_4{}^{3-}$, $F_{29,\,2}= 1.494$, $p = 0.2403$; NO3-N, $F_{12,2} = 0.4459$, $p = 0.6505$; and NH4-N, $F_{29,2} = 1.267$, $p = 0.2969$). Dissolved oxygen contents of the reservoirs were within the optimum range that sustain aquatic life. The DO levels together with high concentrations of nitrates-nitrogen found in reservoirs suggest that high photosynthetic activity occurs in the reservoirs, and confirms the eutrophication and algal bloom occurrence in the reservoirs. The smallest shallow (Golinga) reservoir is significantly impacted by anthropogenic activities than the two reservoirs as indicated by the high levels of DOC, TDNb, NO2-N and turbidity in the Golinga reservoir. Anthropogenic activities such as farming, animal grazing and dumping of domestic wastes are the main sources of pollution in the reservoirs. Effective regulations are thus needed to protect the reservoirs shorelines and catchment areas against degradation and potential future threats.

Keywords: Anthropogenic activities, eutrophication, photosynthetic activity, physicochemical parameters, seasons.

3.1 Introduction

Understanding the spatial and seasonal variations in environmental variables of reservoirs is important for inland fisheries valuation, assessment and management. Several studies have focused on describing the relationships between fisheries (catch per unit effort, biomass, or abundance), socio-economic drivers of fishing and environmental conditions (Cardinale and Arrhenius, 2000; de Mérona and Gascuel, 1993; Mangi et al., 2007; Petry et al., 2003; Schaefer, 1957; Skud, 1982; Whitfield and Elliott, 2002). However, these studies are mainly on marine ecosystems and those on freshwaters are limited to riverine systems. Modelling fish catch in reservoirs with key environmental factors may enhance knowledge on the complexity of the ("unknown") bio-ecological interactions that exist in reservoir fisheries. Several physical and chemical factors influence fish production in freshwater systems. In tropical freshwaters, it has been established that water level fluctuations influence the abundance of fishes (Abobi et al., 2013; Alhassan et al., 2016; Amarasinghe, 1987; Amarasinghe and Pitcher, 1986; Blay and Asabere-Ameyaw, 1993; Braimah, 1995; Quarcoopome et al., 2008). Climatic and hydrological characteristics of drylands are also known to influence fish production (Kolding et al., 2016).

Most reservoirs are annually filled to capacity during the flood season and, because of water loss through evaporation, seepage and discharge either from spill-ways or outlet channels for either irrigation or power generation, the water level drops drastically during the dry season resulting in a marked reduction in reservoir volume and exposure of a vast area of reservoir floor (Ita, 1993). Available evidence indicates that the year-to-year variations in fish stock abundance are directly linked to the degree of variability of the hydrological regime (Welcomme, 1985). However, in stable systems such as reservoirs, rivers or those with flood control the magnitude of the standing stock varies little from year to year, but it is apparent that the catches from flood systems fluctuate in a manner that is in some way dependent on changes in the flood cycle. Reservoirs, on the contrary, experience within-year variation. Wishard (1978) observed that the weighted average monthly fish landings were inversely related to the mean water level of riverine ecosystems.

FAO (2016a) reiterated the relationships between chlorophyll concentrations as a measure of freshwater primary production and fishery yields worldwide and are now using remotely sensed chlorophyll data at the global scale to predict lake yields. A study on Black Volta in Ghana depicts a relationship between catch per unit of effort (cpue) levels, chlorophyll *a* and water level

(Alhassan et al., 2016). Fish production varies with nutrient flux. Van Zwieten et al. (2011) suggested that high productivity of the Volta reservoir can be attributed to the annual flooding of large tracts of land, as the riverine and reservoir waters are relatively low in nutrient concentrations. The authors further indicated that the large annual variations in flooding, including years in which no recession takes place, suggest that the annual production of fish may vary accordingly.

The objectives of the study were to: (i) assess spatial and seasonal differences in physicochemical characteristics of Tono, Bontanga and Golinga reservoirs, (ii) evaluate the environmental quality of the reservoirs and (iii) relate differences in physicochemical characteristics to the management of the reservoirs' catchment areas and fish production.

3.2 Materials and methods

3.2.1 **Reservoir systems**

The study was carried out at three reservoirs: Tono (10° 52' 48" N; 1° 9' 36" W), Bontanga (9° 33' 0" N; 1° 1' 12" W) and Golinga (9° 21' 36" N; 0° 57' 14.4" W) (Fig. 3.1). Tono is the largest reservoir in the Upper East region of Ghana with a surface area of 1,860 ha. Bontanga and Golinga are the largest two reservoirs in the Northern region of Ghana. Bontanga has a surface area of 670 ha, while Golinga is the smallest with an area of 62 ha. Bontanga and Golinga are 20 km apart while Tono is approximately 210 km away from Bontanga and Golinga. Golinga has one landing site, Bontanga has two main landing sites namely Voggu and Bontanga, and Tono has five landing sites (locally called "bays"). The Tono Lake has a length of 3471 m and a catchment area of 650 km^2. The mean depth of the lake is 6.6 m and it has a volume of $93*10^6$ m^3. Bontanga, on the other hand has a length of 1900 m and a catchment area of 165 km^2, mean depth of 5.9 m and a water volume capacity of $25*10^6$ m^3. The mean depth of Golinga reservoir is 2.7 m. The reservoirs are within the Guinea Savanna belt where the most prominent rainy season is from June to October.

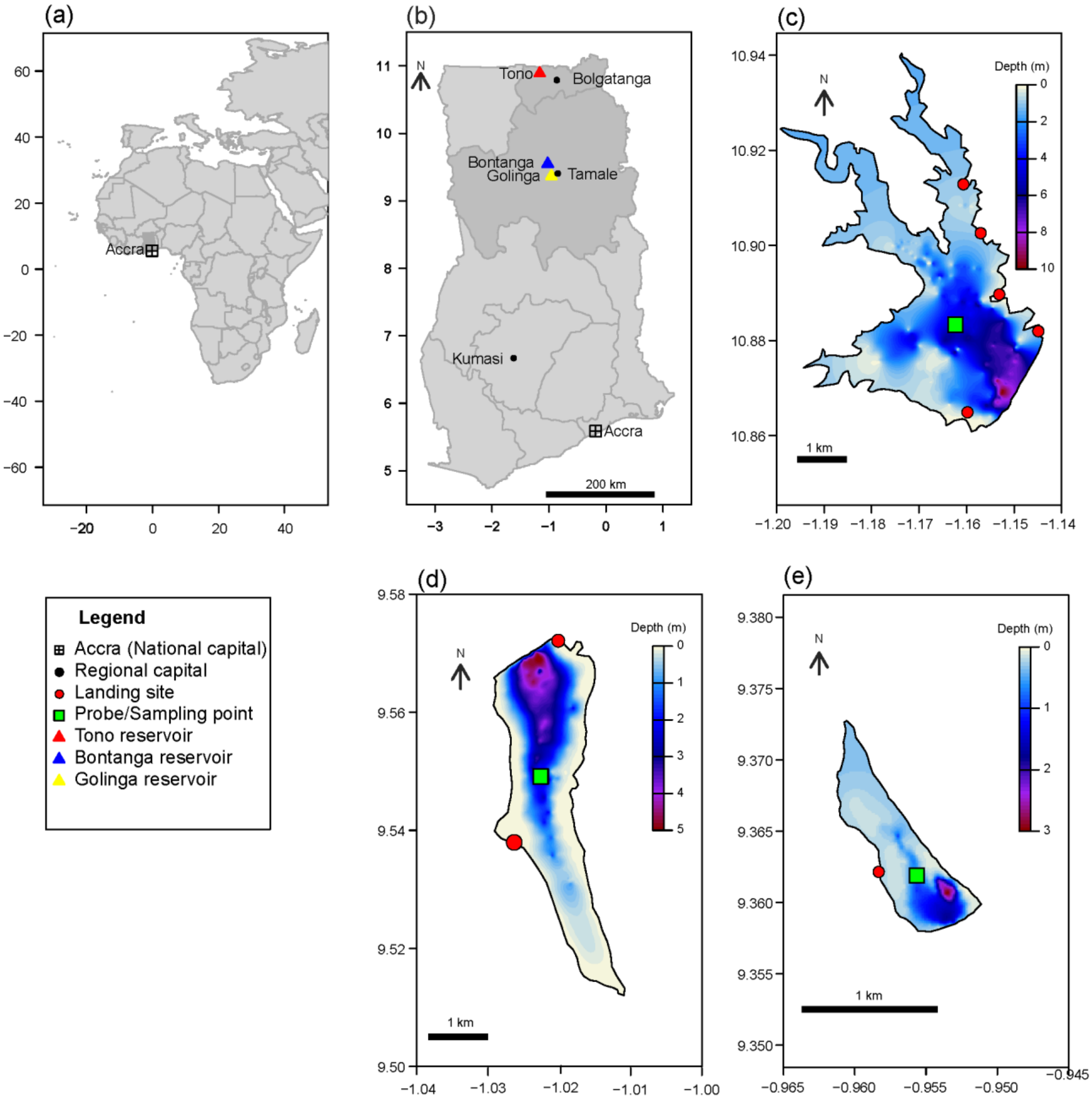

Figure 3.1. Overview maps of the African continent (a) and Ghana (b), indicating the location of national and regional capital cities, as well as the three reservoirs studied in this work. The bathymetric maps of Tono (c), Bontanga (d) and Golinga (e) reservoirs in Ghana, showing landing sites and points (green boxes) where physicochemical characteristics of the reservoirs were monitored. The bathymetric data were obtained during the dry season (March-April 2017).

3.2.2 Study and sampling approach

To understand how seasonal variation in the environmental variables of Tono, Bontanga and Golinga reservoirs, data on chlorophyll *a* (Chl-*a*), dissolved oxygen (DO), temperature, turbidity, Secchi disk depth (SDD) (i.e. water transparency), conductivity, pH, water level and nutrients were collected from July 2016 to June 2017. A two-level sampling approach was adopted for the study. The first level is defined by four hydrological seasons in northern Ghana: dry season (January-March), pre-wet season (April-June), wet season (July-September) and post-wet season (October-December) (Abban et al., 2000). The second level was based on lake size (Large reservoir (Tono), medium-sized reservoir (Bontanga) and small reservoir (Golinga)).

3.2.3 Measurement of physicochemical parameters

The physicochemical parameters: chlorophyll *a*, temperature, electrical conductivity, dissolved oxygen, pH and turbidity were monitored in situ using OTT Hydrolab DS5X multi-parameter water quality probe. The water quality of reservoirs was monitored for 24 hours in each month and the data were logged every 30 minutes. The probe was suspended at a depth of 2m in all the three reservoirs with the aid of solid rectangular foam and a measured length of static rope. The probe was deployed either between 8:00 and 9:00 GMT or between 16:00 and 17:00 GMT and retrieved the next day within the same time period of deployment. Secchi disc was used to measure water transparency. The water level was measured monthly from fixed graduated poles positioned at the dam walls of the reservoirs. Using GARMIN GPSMAP 78s and SPEEDTECH SM5 Depthmate Portable Depth Sounder, XYZ data were collected between March and April 2017 (lowest water level) to generate bathymetric maps for the reservoirs. Water samples were collected using Hydrobios Niskin-Type general purpose water sampler at the same depth as the multi-parameter water quality probe. The water was filtered using 0.45 µm Sartorius Minisart NML syringe filters. Nutrient samples were filtered into clear 50ml polyethylene bottles and were immediately preserved with Mercury (II) Chloride (HgCl2). Dissolved organic carbon samples were stored after filtration in 24mL glass vials with seal and lids without a hole, and preserved with 32% HCl. For Chlorophyll *a* sample, depending on the water turbidity, either 250 or 500 ml of water was filtered using Whatman Glass Microfibers Filter (diameter 25mm and porosity of 0.7 µm) under subdued light and a pressure set by 700mbar. The filters with the Chlorophyll a were carefully folded in four and wrapped with aluminium foil. The samples were stored with ice cubes at the field and transported to the laboratory where they were stored at -20°C until further analysis.

The nutrients were analysed using TECAN-plate reader, while dissolved organic carbon samples were analysed using a combustion analyzer (TOC-V, Shimadzu) and Chlorophyll *a* samples were first extracted with 96% Ethanol at 78°C for 30min and then cooled overnight, after which the samples were analysed using a UV-VIS spectrophotometer (UV-1700, Shimadzu).

3.2.4 **Data analysis**

We tested for the effects of 'Lake' (with three levels: Tono, Bontanga and Golinga) on a set of abiotic parameters: chlorophyll a, dissolved oxygen, ortho-Silicate (o-$SiO_4{}^{4-}$), ortho-Phosphate (o-$PO_4{}^{3-}$), nitrogen (NOx), electrical conductivity, pH, temperature, turbidity, Secchi depth (transparency), dissolved organic carbon (DOC) and total dissolved nitrogen bonded (TDNb). We also tested for the combined effect of lake and season. For all models, we used linear models with Gaussian error terms. Prior to the analyses, the data were log-transformed if needed, to meet the assumptions of normal distribution and homogeneous variances of the residuals (checked through visual inspection of qq plots of the residuals and scatterplots of the fitted data plotted against the residuals). We also checked Cook's distance, dffits (Cohen and Cohen, 2008) where data points were excluded one by one from the data sets and the derived fitted values are compared with those obtained from the models based on all data points, and finally leverage (Quinn and Keough, 2002) for influential data points. Overall, the checks (Cooks distance and dffits) confirmed no influential cases to exist. When checking the leverage, however, some influential deviations in the models were detected. This instability is likely to be on account of the unbalanced data size and was therefore acknowledged. Nonetheless, the results were interpreted with caution. Pairwise post-hoc comparisons were run to test for individual differences between factor levels. The models were fitted in R, version 3.6.0 (Team, 2019), using the generic function 'lm'. Seasonal variation was tested for the parameters monitored using the OTT Hydrolab DS5X multi-parameter water quality probe (i.e. chlorophyll *a*, dissolved oxygen, electrical conductivity, temperature and turbidity and pH) and Secchi depth transparency due to the high sample size of these parameters. For the parameters analysed in the laboratory (i.e. o-$PO_4{}^{3-}$, NO3-N, NO2-N, NH4-N, o-$SiO_4{}^{4-}$, DOC and TDNb), the statistical tests were limited to spatial variation between the lakes.

3.3 Results

3.3.1 Chlorophyll a (*Chl-a*)

The average seasonal concentrations of Chl-*a* ranged from 2.35 ± 0.05 to 45.9 ± 5.35 mg m^{-3}, with significantly higher mean values across the reservoirs during the post-wet and dry season compared to the pre-wet and wet seasons (Figure 3.2a, Table 3.1). Between the reservoirs, there were no significant differences in Chl-*a* concentration during the wet and post-wet seasons. However, Chlorophyll *a* concentration during the dry season was significantly different between the reservoirs, with Golinga having the highest Chlorophyll *a* concentration, followed by Bontanga, and then Tono with the lowest concentration. During the pre-wet season, Chlorophyll *a* concentration in Golinga was significantly higher than the concentration measured in Tono, while the concentration of Bontanga was immediate and not significantly different from the concentrations of Tono and Golinga reservoirs (Table 3.1).

3.3.2 Dissolved oxygen

The average seasonal dissolved oxygen concentrations in the reservoirs ranged between 5.45 ± 0.06 to 9.11 ± 0.13 mg L^{-1} (Table 3.1). Dissolved oxygen showed a decreasing trend from the wet season to the dry season across the reservoirs, followed by an increase in the DO levels during the pre-wet season (Figure 3.2b). DO levels between the reservoirs during the wet, post-wet and pre-wet seasons were significantly different, with Bontanga and Tono, respectively, having the highest and the lowest DO levels during both the wet and post-wet seasons, while in the pre-wet season, Tono and Golinga had the highest and lowest DO levels, respectively. During the dry season, DO levels in Bontanga and Golinga reservoirs were not significantly different, but DO levels of both reservoirs were significantly higher than the DO levels of Tono reservoir (Table 3.1).

3.3.3 Temperature

The temperature of the reservoirs ranged seasonally from 25.8 ± 0.33 to 31.27 ± 0.10 °C (Table 3.1). In Tono and Bontanga reservoirs, temperature levels were highest during the pre-wet season, while in the smallest shallow reservoir (Golinga), the highest temperatures were measured during the dry season (Figure 3.2c). The lowest temperature levels were recorded in the post-wet season, dry season and wet season in Tono, Bontanga and Golinga, respectively (Figure 3.2c). During the wet season, the temperature of Bontanga was significantly higher than the temperature levels of Tono and Golinga, and the temperature of Golinga was also significantly higher than the temperature levels measured in Tono. During the post-wet season, the temperature levels of Bontanga and Golinga reservoirs were similar (no significant difference). However, the temperature of Tono was significantly lower than the levels measured in both Bontanga and Golinga. Temperature levels varied significantly between the three reservoirs during the dry and pre-wet seasons, with Golinga, Bontanga and Tono, having the highest, immediate and lowest temperature levels, respectively, during the dry season, and Tono, Bontanga and Golinga, recording the highest, immediate and the lowest temperature levels, respectively, during the pre-wet season (Table 3.1).

3.3.4 **Turbidity**

The average seasonal turbidity levels of the reservoirs ranged from 42 ± 0.22 to 544 ± 32.03 NTU. The trends of seasonal variation in turbidity found in Tono and Bontanga reservoirs were similar, as the turbidity levels of both reservoirs' waters measured during the wet season (i.e. the season with the highest turbidity in both reservoirs) decreased in the post-wet and the dry seasons, followed by a minimal increase during the pre-wet season. In contrast, Golinga had high turbid waters during the wet season, and then reduced during the post-wet and dry seasons. The turbidity of Golinga reservoir waters rose sharply to the highest level during the pre-wet season (Figure 3.3a). During the wet season, the turbidity of Tono was significantly higher than the turbidity levels of Golinga and Bontanga; and the turbidity of Golinga was also significantly higher than the levels measured in Bontanga. During the post-wet season, there were no differences in turbidity between the three reservoirs. In the dry season, the turbidity was significantly higher in Golinga than Bontanga, but not significantly different from that of Tono. The turbidity of Tono was immediate and also not significantly from that of Bontanga. During the pre-wet season, the turbidity of Golinga was extremely and significantly higher than the turbidity levels of Tono and Bontanga. Both Tono and Bontanga did not differ significantly during the pre-wet season (Table 3.1).

3.3.5 **Secchi disk depth (transparency)**

The Secchi disk depths (SDD) of the reservoirs ranged from 5.77 ± 0.95 to 91.95 ± 1.50 cm. The trend of Secchi depth was the same across the reservoirs as the water transparency increased from the wet season to the highest level during the dry season (i.e. the season with the most transparent water column), followed by a decrease in transparency level in the reservoirs during the pre-wet season (Figure 3.3b). During the wet season, the SDD values of Tono was significantly higher than Golinga and Bontanga; and the Secchi depth of Golinga was also significantly higher than the SDD values measured in Bontanga. During the post-wet season, the SDD value of Bontanga was significantly lower than the values measured in Tono and Golinga. There was no difference in SDD values measured in Tono and Golinga during the post-wet season. Secchi disk depths of Tono and Bontanga did not differ significantly during the dry season. However, the Secchi depth of Golinga was significantly lower than the values of Tono and Bontanga during the dry season. During the pre-wet season, SDD values differed significantly across the reservoirs, with Tono, Bontanga and Golinga, recording the highest, immediate and lowest values, respectively (Table 3.1).

3.3.6 **Electrical conductivity**

The electrical conductivity levels of the reservoirs ranged from 47.63 ± 1.00 to 129.53 ± 0.16 µS cm^{-1}. The electrical conductivity trend was similar across the reservoirs, with concentrations increasing from the wet season to the dry season, and a decrease in the concentrations during the pre-wet season. However, the decrease during the pre-wet season was more pronounced in Golinga and Bontanga reservoirs than Tono reservoir (Figure 3.3c). In all seasons, electrical conductivity differed significantly across the reservoirs. During the wet season, Golinga, Bontanga and Tono had the highest, immediate and lowest electrical conductivity levels, respectively. During both the pre-wet and dry seasons, Golinga, Tono, and Bontanga had the highest, immediate and lowest electrical conductivity levels, respectively. During the pre-wet season, Tono, Golinga and Bontanga had the highest, immediate and lowest electrical conductivity levels, respectively (Table 3.1).

3.3.7 **Hydrogen ion concentration (pH)**

The hydrogen ion concentration (pH) of the reservoirs ranged from 6.90 ± 0.07 to 7.91 ± 0.10. The hydrogen ion concentration of the reservoirs' waters depicted an increasing trend from the wet season to the pre-wet season in Tono and Bontanga reservoirs, while in Golinga, the increasing pH peaked during the dry season, and subsequently, decreased during the pre-wet season (Figure 3.3d). pH levels across the reservoirs did not differ significantly during the wet and dry seasons. During the post-wet season, the pH was significantly higher in Tono reservoir than in Bontanga and Golinga. In Bontanga and Golinga, it did not differ significantly. During the pre-wet season, pH differed significantly across the reservoirs, with Bontanga, Tono and Golinga having the highest, immediate and lowest values, respectively (Table 3.1).

The details on significant differences in seasonal variation of physicochemical characteristics within each reservoir can be found on Table 3.2.

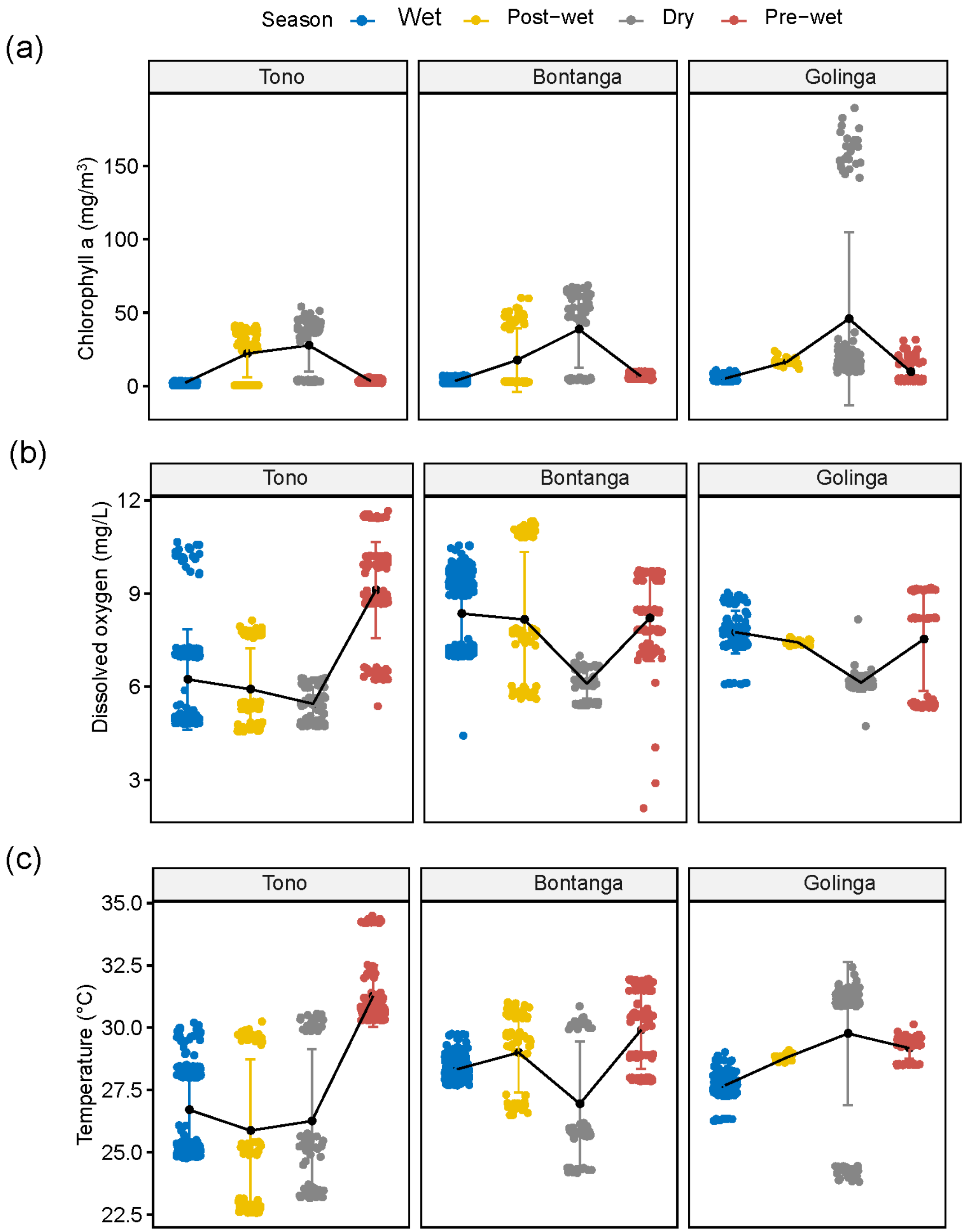

Figure 3.2. Seasonal variation in Chlorophyll a (a), dissolved oxygen (b) and temperature (c) in Tono, Bontanga and Golinga reservoirs. Wet season-July 216-September 2016; Post-wet season-October 2016-December 2016; Dry season-January 2017-March 2017; and Pre-wet season-April 2017-June 2017. The black dots and the coloured vertical lines represent the sample mean and standard deviation, respectively.

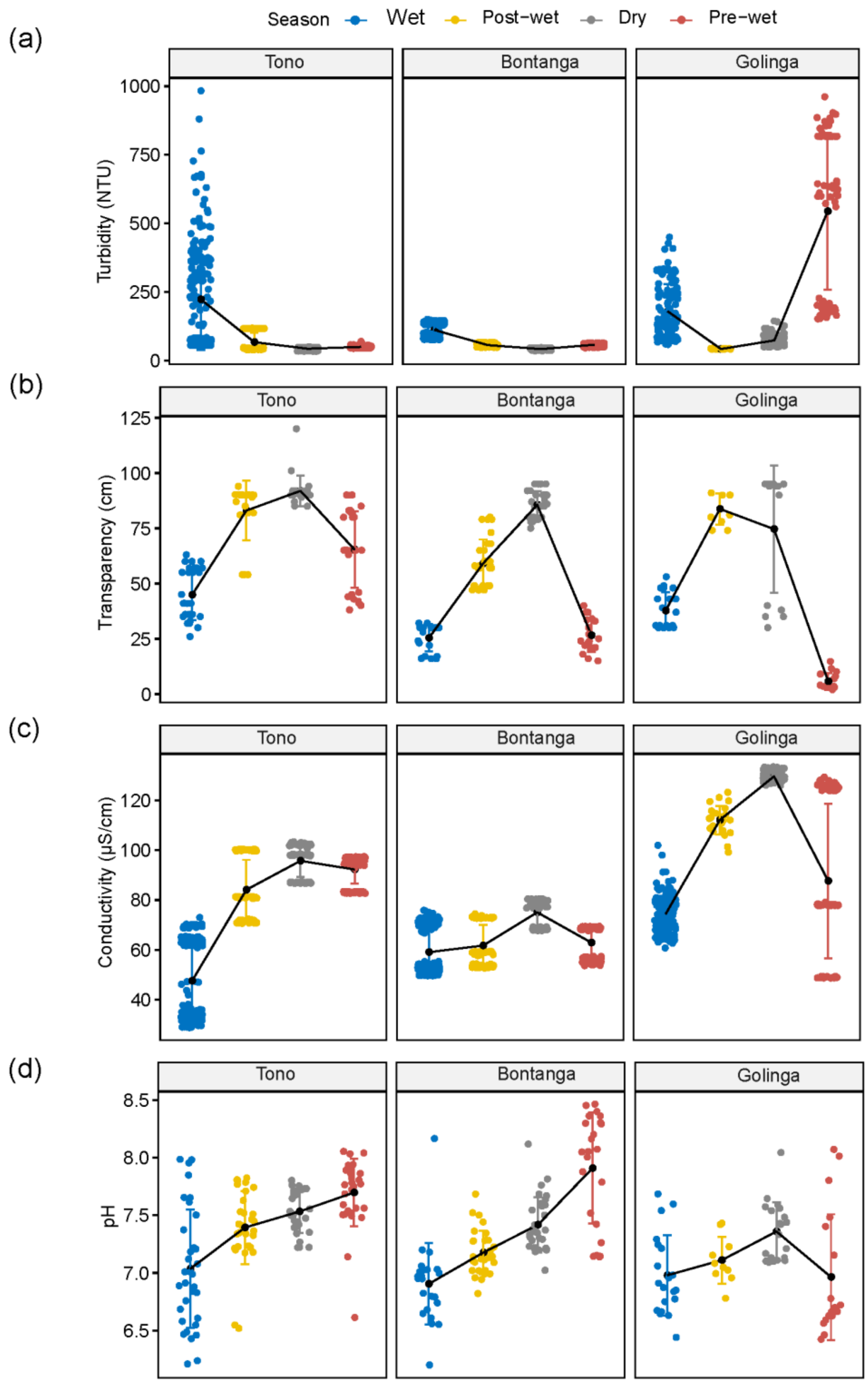

Figure 3.3. Seasonal variation in turbidity(a), transparency (b), conductivity (c) and pH (d) in Tono, Bontanga and Golinga reservoirs. Wet season-July 216-September 2016; Post-wet season-October 2016-December 2016; Dry season-January 2017-March 2017; and Pre-wet season-April 2017-June 2017. The black dots and the coloured vertical lines represent the sample mean and standard deviation, respectively.

Table 3.1. Seasonal variation in physicochemical characteristics between the reservoirs. Figures on the same row with different superscript letters within a season column are significantly different. α at 5% significance level.

Parameters	Wet season			Post-wet season			Dry season			Pre-wet		
	Tono	Bontanga	Golinga	Tono	Bontanga	Golinga	Tono	Bontanga	Golinga	Tono	Bontanga	Golinga
Chlorophyll a	2.35^a	3.58^a	5.24^a	22.15^a	17.74^a	16.62^a	27.77^a	38.72^b	45.90^c	3.51^a	6.83^{ac}	9.73^c
(mg m^{-3})	± 0.05	± 0.11	± 0.15	± 1.88	± 2.49	± 0.54	± 2.07	±3.14	± 5.35	± 0.07	± 0.21	± 0.87
DO	6.23^a	8.35^b	7.75^c	5.92^a	8.16^b	7.42^c	5.45^a	6.10^b	6.13^b	9.11^a	8.21^b	7.53^c
(mg L^{-1})	± 0.10	± 0.07	± 0.06	± 0.15	± 0.25	± 0.01	± 0.06	± 0.06	± 0.03	± 0.13	± 0.14	± 0.19
Temperature	26.71^a	28.34^b	27.69^c	25.8^a	29.00^b ± 0.18	28.80^b	26.26^a	26.95^b	29.77^c	31.27^a	29.92^b ± 0.15	29.18^c
(°C)	± 0.11	± 0.02	± 0.05	± 0.33		± 0.02	± 0.33	± 0.30	± 0.26	± 0.10		± 0.05
Turbidity	222.6^a	111.5^b	180^c	67.0^a	56.3^a	42^a	42.9^{ab}	41.5^b	73.3^a	49.7^a	57.5^a	544^b
(NTU)	± 11.85	± 1.52	± 8.22	±4.05	± 0.77	± 0.22	± 0.69	± 0.43	± 1.68	± 0.29	± 0.50	± 32.03
Transparency	44.93^a	25.42^b	37.75^c	83.03^a	59.10^b	83.80^a	91.95^a	85.64^a	74.67^b	65.36^a	26.64^b	5.77^c
(cm)	± 2.14	± 1.42	± 1.85	± 2.46	± 1.98	± 2.24	± 1.50	± 1.15	± 7.41	± 3.26	± 1.80	± 0.95
Conductivity	47.63^a	59.11^b	74.39^c	84.09^a	61.76^b	112.08^c	95.71^a	75.07^b	129.53^c	92.240^a	62.94^b	87.65^c
(µS cm^{-1})	± 1.00	± 0.55	± 0.58	± 1.39	± 0.96	± 1.14	± 0.74	± 0.62	± 0.16	± 0.45	± 0.64	± 3.47
pH	7.04^a	6.90^a	6.98^a	7.39^a	7.18^b	7.11^b	7.53^a	7.42^a	7.36^a	7.70^a	7.91^b	6.96^c
(pH units)	± 0.09	± 0.07	± 0.08	± 0.06	± 0.03	± 0.06	± 0.04	± 0.04	± 0.06	± 0.05	± 0.10	± 0.10

Table 3.2. Seasonal variation in physicochemical characteristics within the reservoirs. (Mean ± standard error). Figures on the same row with different superscript letters within a lake column are significantly different. α at 5% significance level.

Parameters	Tono				Bontanga				Golinga			
	Wet	Post-wet	Dry	Pre-wet	Wet	Post-wet	Dry	Pre-wet	Wet	Post-wet	Dry	Pre-wet
Chlorophyll *a* (mg m^{-3})	2.35^{a} ± 0.05	22.15^{b} ± 1.88	27.77^{b} ± 2.07	3.51^{a} ± 0.07	3.58^{a} ± 0.11	17.74^{b} ± 2.49	38.72^{c} ±3.14	6.83^{a} ± 0.21	5.24^{a} ± 0.15	16.62^{b} ± 0.54	45.90^{c} ± 5.35	9.73^{b} ± 0.87
DO (mg L^{-1})	6.23^{a} ± 0.10	5.92^{a} ± 0.15	5.45^{b} ± 0.06	9.11^{c} ± 0.13	8.35^{a} ± 0.07	8.16^{a} ± 0.25	6.10^{b} ± 0.06	8.21^{a} ± 0.14	7.75^{a} ± 0.06	7.42^{a} ± 0.01	6.13^{b} ± 0.03	7.53^{a} ± 0.19
Temperature (°C)	26.71^{a} ± 0.11	25.8^{a} ± 0.33	26.26^{b} ± 0.33	31.27^{c} ± 0.10	28.34^{a} ± 0.02	29.00^{b} ± 0.18	26.95^{c} ± 0.30	29.92^{d} ± 0.15	27.69^{a} ± 0.05	28.80^{b} ± 0.02	29.77^{c} ± 0.26	29.18^{b} ± 0.05
Turbidity (NTU)	222.6^{a} ± 11.85	67.0^{b} ±4.05	42.9^{b} ± 0.69	49.7^{b} ± 0.29	111.5^{a} ± 1.52	56.3^{b} ± 0.77	41.5^{b} ± 0.43	57.5^{b} ± 0.50	180^{a} ± 8.22	42^{b} ± 0.22	73.3^{b} ± 1.68	544^{c} ± 32.03
Transparency (cm)	44.93^{a} ± 2.14	83.03^{b} ± 2.46	91.95^{c} ± 1.50	65.36^{d} ± 3.26	25.42^{a} ± 1.42	59.10^{b} ± 1.98	85.64^{c} ± 1.15	26.64^{a} ± 1.80	37.75^{a} ± 1.85	83.80^{b} ± 2.24	74.67^{b} ± 7.41	5.77^{c} ± 0.95
Conductivity (µS cm^{-1})	47.63^{a} ± 1.00	84.09^{b} ± 1.39	95.71^{c} ± 0.74	92.240^{d} ± 0.45	59.11^{a} ± 0.55	61.76^{ab} ± 0.96	75.07^{c} ± 0.62	62.94^{b} ± 0.64	74.39^{a} ± 0.58	112.1^{b} ± 1.14	129.5^{c} ± 0.16	87.65^{d} ± 3.47
pH (pH units)	7.04^{a} ± 0.09	7.39^{b} ± 0.06	7.53^{bc} ± 0.04	7.70^{c} ± 0.05	6.90^{a} ± 0.07	7.18^{b} ± 0.03	7.42^{c} ± 0.04	7.91^{d} ± 0.10	6.98^{a} ± 0.08	7.11^{ab} ± 0.06	7.36^{b} ± 0.06	6.96^{a} ± 0.10

3.3.8 Orthophosphate, nitrate-nitrogen, nitrite-nitrogen, ammonium-nitrogen, orthosilicate, dissolved organic carbon and total dissolved nitrogen bonded

The Analysis of variance (ANOVA) results on spatial variation in ortho-Phosphate (o-PO_4^{3-}), Nitrate nitrogen (NO3-N), Nitrite nitrogen (NO2-N), Ammonium-nitrogen (NH4-N), ortho-Silicate (o-SiO_4^{4-}), dissolved organic carbon (DOC) and total dissolved nitrogen bonded (TDNb) concentrations between the lakes are presented in Table 3.3.

The ANOVA tests showed non-significant results in o-PO_4^{3-}, NO3-N and NH4-N concentrations between the reservoirs (o-PO_4^{3-}, $F_{29, 2}$= 1.494, p = 0.2403; NO3-N, $F_{12,2}$ = 0.4459, p = 0.6505; and NH4-N, $F_{29,2}$ = 1.267, p = 0.2969). This indicates that neither of the lakes studied was different with respect to o-PO_4^{3-}, NO3-N and NH4-N concentrations. NO2-N concentrations did not differ between Tono and Bontanga (p= 0.199, Tono=0.0064 mg L^{-1}, Bontanga=0.012 mg L^{-1}); and Bontanga and Golinga (p=0.2122, Bontanga=0.012 mg L^{-1}, Golinga=0.033 mg L^{-1}). However, NO2-N concentration of Golinga was significantly higher than Tono (p=0.0176, Golinga=0.033 mg L^{-1}, Tono=0.0064 mg L^{-1}). For o-SiO_4^{4-}, the overall outcome of the ANOVA revealed a significant result ($F_{29,2}$ = 7.252, p = 0.002792). There were differences between the lakes: o-SiO_4^{4-} in Lake Tono (0.762 mg L^{-1}) was significantly higher than the concentrations in the other two lakes (Bontanga, p=0.00284, o-SiO_4^{4-}=0.304 mg L^{-1}; and Golinga, p=0.00243, o-SiO_4^{4-}=0.329 mg L^{-1}), but Lake Golinga and Lake Bontanga did not differ with respect to o-SiO_4^{4-} (p = 0.75103). DOC concentration of Golinga (533.63 µM) was significantly higher than the concentrations of the other two lakes (Tono, p=0.00977, DOC=350.02 µM; and Bontanga, p=0.01084, DOC=359.40 µM). DOC concentrations of Tono and Bontanga did not differ (p=0.91418). Similarly, the overall outcome of ANOVA of TDNb revealed a significant result ($F_{27,2}$ = 6.798, p = 0.004063). TDNb in Lake Golinga (80.22 µM) was significantly higher than the other two lakes (Tono, p= 0.00108, TDNb =31.98 µM; and Bontanga, p= 0.02685, TDNb=44.4 µM). Lake Bontanga and Lake Tono did not differ with respect to TDNb (p = 0.16102).

Table 3.3. Variation in o-$PO_4{}^{3-}$, NO3-N, NO2-N, NH4-N, o-$SiO_4{}^{4-}$, DOC and TDNb in Tono, Bontanga and Golinga reservoirs based on sampling conducted between July 2016 and June 2017 (Mean ± Confidence interval). Figures on the same row with different superscript letters are significantly different. α at 5% significance level.

Parameter/Reservoir	Tono	Bontanga	Golinga
o-$PO_4{}^{3-}$ (mg L^{-1})	$0.371^{a} \pm 0.036$	$0.491^{a} \pm 0.033$	$0.293^{a} \pm 0.035$
NO3-N (mg L^{-1})	$2.402^{a} \pm 0.144$	$2.477^{a} \pm 0.192$	$1.618^{a} \pm 0.119$
NO2-N (mg L^{-1})	$0.0064^{a} \pm 0.0034$	$0.012^{ab} \pm 0.0034$	$0.033^{b} \pm 0.0035$
NH4-N (mg L^{-1})	$0.101^{a} \pm 0.0081$	$0.202^{a} \pm 0.0084$	$0.208^{a} \pm 0.0086$
o-$SiO_4{}^{4-}$ (mg L^{-1})	$0.762^{a} \pm 0.020$	$0.304^{b} \pm 0.0195$	$0.329^{b} \pm 0.021$
DOC (µM)	$350.02^{a} \pm 19.54$	$359.40^{a} \pm 19.14$	$533.63^{b} \pm 18.79$
TDNb (µM)	$31.99^{a} \pm 2.50$	$44.44^{a} \pm 2.45$	$80.22^{b} \pm 2.41$

3.4 **Discussion**

The reservoirs can be considered eutrophic during the post-wet and dry seasons as indicated by the high levels of Chl-*a.* The Chl-*a* concentrations during the post-wet and dry seasons were above the desirable limit of 7-10 mg m^{-3} for tropical reservoirs (Araújo et al., 2011; Fondriest, 2014). The dissolved oxygen concentrations in the reservoirs were within the acceptable limits that support many aquatic animals, which indicate healthy ecosystems. The high DO levels of the reservoirs suggest that 'fish kill' in the reservoirs is unlikely if the levels are maintained. Behar et al. (1997) indicated that dissolved oxygen concentration of (i) 0-2 mg L^{-1} is not enough oxygen to support life; (ii) 2-4 mg L^{-1} can sustain only a few fish and aquatic insects; (iii) 4-7 mg L^{-1} is good for many aquatic animals, but low for cold water fish; and (iv) 7-11 mg L^{-1} is very good for most stream fish. The temperatures of the reservoirs were within ranges, typical of man-made reservoirs in Ghana. Quarcoopome et al. (2008) reported mean annual temperatures of 29.7 °C and 30.2 °C in Bontanga and Libga reservoirs, respectively, which are within the temperature range of this study. Webb (1960) indicated that in the tropics, rainfall is more important than temperature in determining environmental quality. According to Behar et al. (1997), the largest variety of freshwater aquatic organisms prefer a pH range between 6.5 to 8.0. pH levels of Tono, Bontanga and Golinga reservoirs were within this range across all the four seasons. The transparency trend of the studied reservoirs (high transparency recorded during the dry season (Jan-Mar) as compared to the wet season (Jul-Sep)) is similar to the pattern observed in a tropical reservoir (Funil) in Brazil (Araújo et al., 2011). The conductivity levels of the reservoirs (average seasonal concentration of conductivity ranged from 47.63 ± 1.00 to 129.53 ± 0.16 $\mu S\ cm^{-1}$) were low conductivity. Kotut et al. (1999) found that conductivity levels in Turkwell Gorge Reservoir (Kenya) ranged from 160 to 200 $\mu S\ cm^{-1}$. The nitrate levels found in the reservoirs were not above the limit of 10 $mg\ L^{-1}$. According to Behar et al. (1997), concentrations over 10 $mg\ L^{-1}$ may have an effect on the freshwater aquatic environment. The average phosphate contents of the reservoirs (Table 3.3) were above the range of 0.02-0.29 $mg\ L^{-1}$ recorded in the Bui dam area of the Black Volta in Ghana (Alhassan et al., 2015), but were low the phosphate content range of 0.5-0.75 mg L^{-1} recorded in Asejire reservoir in Nigeria (Egborge, 1979). The significantly higher values of turbidity recorded during the rainy season is attributed to surface runoffs. During the rainy season, runoffs from agriculture fields and other urban sources introduce high loads of suspended matter into reservoirs (Asante et al., 2008).

Chl-a concentrations of the reservoirs were similar during the wet, post-wet and pre-wet seasons, while during the dry season, concentrations were significantly different, with Golinga recording the highest concentration of Chl-a, followed by Bontanga, and then Tono (the lowest concentration). The variation could be attributed to differences in organic matter inputs into the reservoirs. The high Chl-a contents of Golinga during dry season is reflected in the extremely and significantly higher turbidity levels recorded in the reservoirs in the proceeding pre-wet (Apr-Jun), as it has been stated that as occurrence of algae and aquatic weeds contribute to high turbid waters (Asante et al., 2008). Considering the high levels of DOC, TDNb, NO2-N and turbidity, it is evident that the smallest shallow (Golinga) reservoir is significantly impacted than the other two reservoirs.

The main management implication of our results is that the control of runoffs from agricultural fields is important in maintaining healthy reservoir ecosystems. Farming practices such as ploughing of land, slash and burn, and animal grazing in the catchment areas of the reservoirs are sources of phosphate. Moreover, these practices contribute to high turbidity and eutrophication in the reservoirs, which may adversely impact the aquatic organisms.

CHAPTER 4: Assessment of reservoir cichlid fishery

Assessing the exploitation status of main fisheries resources in Ghana’s reservoirs based on reconstructed catches and a length-based bootstrapping stock assessment method

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Abstract

The cichlid species *Oreochromis niloticus*, *Sarotherondon galilaeus*, and *Coptodon zillii*, which are among the most exploited resources in the small-scale fisheries of the Tono, Bontanga, and Golinga reservoirs in northern Ghana, were assessed based on length frequency samples. Growth, mortality, exploitation status, stock size, and relative yield per recruit reference points were determined using bootstrapping fish stock assessment (BFSA), a novel framework that allows for the estimation of uncertainties around the life-history parameters and reference levels (e.g., $L\infty$, K, and $F_{0.1}$). The results suggest that the 3 species studied are heavily exploited in all 3 reservoirs, but with no alarming signs of overexploitation. The fishing effort at Golinga is comparatively low as a result of insignificant fishing during the agriculture season, which relates to low exploitation rates. *Sarotherondon galilaeus* and *C. zillii* have the highest and lowest biomass (t/km^2) respectively in all the 3 reservoirs. The small shallow reservoir (Golinga) has the highest biomass of the target resources per unit area. According to a second assessment approach, based on length-based indicators, all species at Bontanga and *O. niloticus* and *S. galilaeus* populations at Golinga have spawning stock biomasses below 40% of the unfished biomass. This points to a situation of a possible ongoing recruitment overfishing of those species in the 2 reservoirs and suggests that a further increase in fishing effort should be prevented. Further monitoring of these fisheries will be needed for the improvement of assessments and thus management advice.

Key words: BFSA; Ghana; Length-based indicators; Reservoirs; Stock assessment; TropFishR.

4.1 Introduction

Reservoirs, lakes, and rivers are essential food security and livelihood resources. Inland water bodies provide multiple community needs, including domestic water supply, irrigation, hydropower generation, recreation, fisheries and aquaculture harvests (Deines et al., 2017; Lynch et al., 2016). Fish production from inland waters contributed 12.7% to total global capture fishery production in 2014 (FAO, 2016a). The management arrangements for reservoir fisheries in Ghana are no different from what has been noted globally for many inland water bodies. According to FAO and MSU (2016), many inland water bodies are lacking management that can adequately enforce the sustainable use of resources. Additionally, where management arrangements exist, compliance and enforcement are often minimal or non-existent. This may result in excessive fishing pressure, decreased catch per unit effort, conflicts between fishers, and changes in the productivity of fishery resources. As a consequence, reductions in fishing capacity will be required in some areas. To facilitate fishery management, “The Rome Declaration: Ten Steps to Responsible Inland Fisheries” (FAO and MSU, 2016) emphasizes the importance of (i) improving biological and production data assessment; (ii) developing and improving science-based approaches to fishery management; (iii) adequate valuing of inland aquatic systems; and (iv) improving access to and promoting better sharing of data and information about inland fisheries supporting the assessment–management cycle. Following these suggestions, the goal of this research was, to contribute to the development of science-based approaches to reservoir fishery management in Ghana using assessment methods that offer extended and robust information on growth, mortality, exploitation, and stock status.

Fishing is a traditional activity in Ghana, particularly among rural communities along the coastline and the major rivers such as the Volta and its tributaries. Fishing provides a major source of employment and income as well as food for people across the country. Five hundred thousand fishermen, fish processors, traders, and boat builders are employed in the fisheries sector of Ghana. Together with the dependents of these workers, the fisheries sector supports 10 percent of the Ghanaian population (Mensah, 2012). In Northern Ghana, fishes from rivers, reservoirs, and dugouts (constructed water retention ponds) are an important dietary supplement for the people.

The domestic demand for fish in Ghana has been rising in response to human population growth, rising incomes, and urbanization. Fish and fish products, including low-value species like tilapias, are gradually becoming more expensive and inaccessible to the poor, relative to other sources of animal protein. A continuous decline in fisheries production in Ghana's inland waters, paralleled by increasing prices, will have disastrous consequences on food security, livelihoods, and national economy. The national demand for fish is estimated at 880,000 t annually, but approximately 50% is produced locally, leaving a supply deficit of a little over 50%, filled in by fish imports worth over US $200 million (MoFA, 2012). This has become a real concern for policymakers in the fisheries subsector over the years. Fish production statistics by the Ministry of Fisheries and Aquaculture Development show that production from the aquaculture sector has been increasing by 6744 tonnes per year since 2010, while inland fisheries production during the same period has declined by 910 tonnes per year, that is, 1.1% of the average annual inland capture fisheries production. Also, it has been noted that for the past 20 years, catches from the reservoirs in Northern Ghana have been dwindling. Possible reasons for the decline in catch could be overexploitation of stocks, environmental degradation, and low water levels, which would have negatively impacted fish production (Abban et al., 2000; Amevenku and Quarcoopome, 2006). Obodai and Waltia (2003) attributed the lower catches in Tono Reservoir, the largest in the Upper East Region of Ghana, to poor management practices and overexploitation. The Ghanaian Fisheries Act (Fisheries Act, 2002) allows for the declaration of closed seasons in specified areas of coastal waters or riverine system. Attempts by the fisheries commission to implement closed seasons to reservoir systems have generally not been successful in the past. However, the fishers of Tono enforce a ban on fishing at the upstream parts of the reservoir during the peak month (either August or September) of the raining season. Moreover, no fishing activity in the reservoir is allowed between 11:00-16:00 GMT. Fishers are allowed to set gillnets starting from 16:00 GMT and the nets are removed the next day before 11:00 GMT. The use of dynamites or poison for fishing is also prohibited.

The target fisheries of Tono, Bontanga, and Golinga reservoirs have not yet been assessed. Research has mainly focused on fisheries socio-economics, water productivity, sedimentation, and water storage, in particular at Tono (Abache, 2015; Abubakari, 2015; Diekkrüger and Liebe, 2002; Mdemu, 2008; Okrah, 2010). Recent work on the Tono Reservoir by (Akongyuure et al., 2017b) was focused on gillnet selectivity estimates of the target fish species. (Kwarfo-Apegyah, 2008) studied the exploitation rates and management implications of the Bontanga Reservoir fisheries from 2004 to 2006 and reported that the reservoir had 26 fish species belonging to 19 genera in 11 families. Another study by (Quarcoopome et al., 2008), focused on the fisheries and limnology of the Bontanga Reservoir. No fisheries studies have as yet been conducted on the Golinga Reservoir.

This study was aimed at assessing the stock sizes, growth parameters, and exploitation status of the target fish species *Sarotherondon galilaeus* (Linnaeus 1758), *Oreochromis niloticus* (Linnaeus 1758), and *Coptodon zillii* (Gervais 1848) in the Tono, Bontanga, and Golinga reservoirs. The study employed two complementary assessment approaches: (1) the analysis of periodically sampled length frequency data using the TropFishR software to estimate growth, mortality parameters, exploitation rates, stock size, and biological reference points from yield per recruit analysis and (2) the use of length based indicators to estimate the spawning potential of the species under the current exploitation regime.

4.2 Materials and methods

4.2.1 The reservoir systems of Northern Ghana

Northern Ghana is covered in Savannah and has a mono-modal rainfall cycle that is subject to wide variation. Because of intermittent and terminal droughts, crop and animal production can be extremely difficult. To mitigate these challenges, reservoirs were constructed for domestic uses, livestock watering, fish farming, and irrigated agriculture (MoFA, 2018). With time, they have grown into significant inland fishing grounds. This study was carried out at 3 reservoirs: Tono (10° 52' 48" N; 1° 9' 36" W), Bontanga (9° 33' 0" N; 1° 1' 12" W), and Golinga (9° 21' 36" N; 0° 57' 14.4" W) (Fig. 4.1). Tono is the largest reservoir in the Upper East Region of Ghana and has a surface area of 1,860 ha. Bontanga with a surface area of 670 ha is the largest reservoir in the Northern Region of Ghana, while Golinga is the smallest among the 3 reservoirs with an area of 62 ha. Bontanga and Golinga are only 20 km apart while Tono is approximately 210 km away from Bontanga and Golinga (Table 4.1). Golinga has one landing site, Bontanga has 2 landing sites (named Voggu and Bontanga), and Tono has 5 landing sites (locally called "bays").

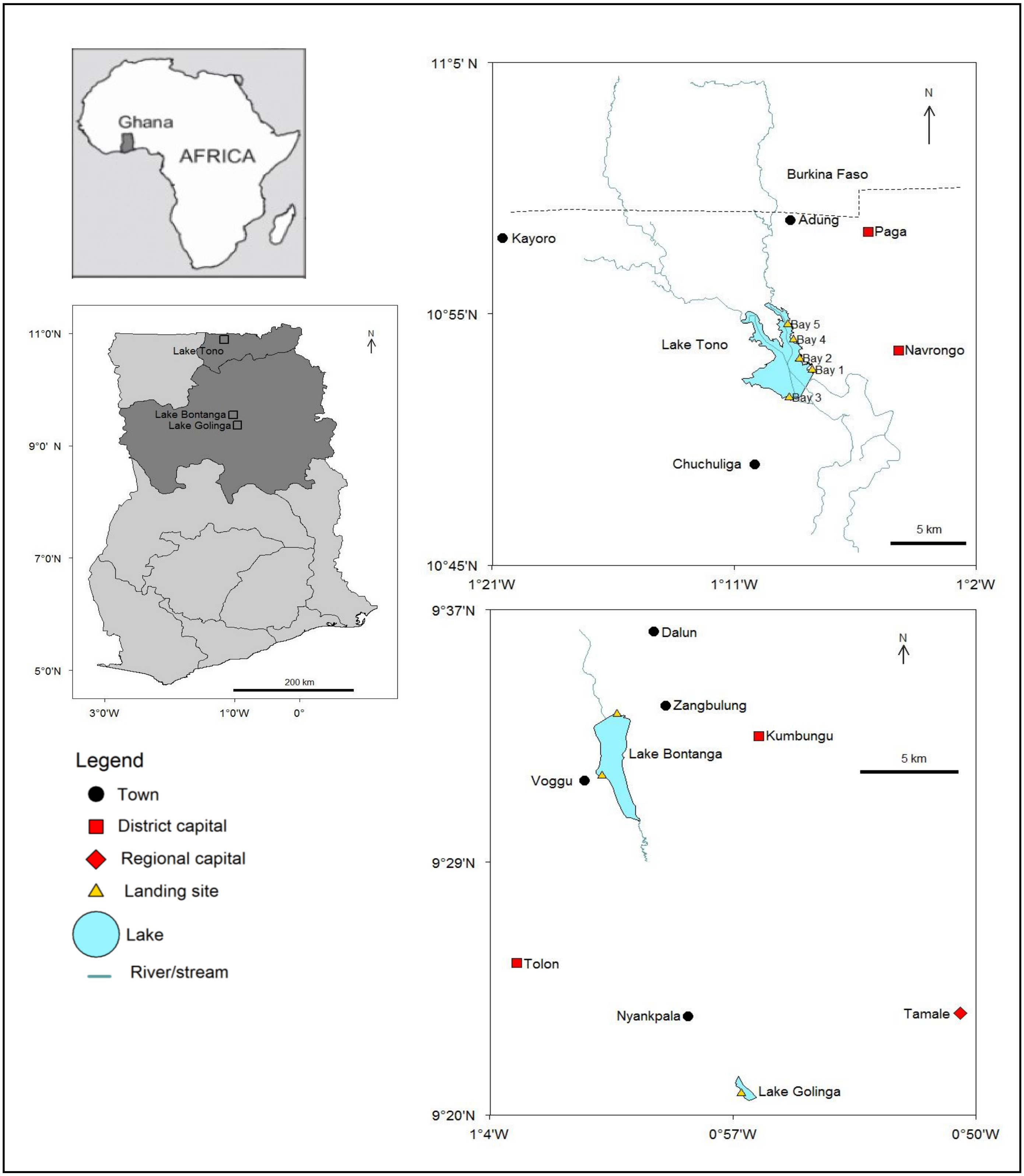


Figure 4.1. Map showing the locations of Tono, Bontanga, and Golinga reservoirs in Ghana.

Table 4.1. Morphometric characteristics of Tono, Bontanga, and Golinga reservoirs.

Parameter	Tono	Bontanga	Golinga
Surface area (km^2)	18.6	6.7	0.62
Reservoir length (m)	3471	1900	690
Mean depth (m)	6.6	5.9	2.7
Maximum depth (m)	13.32	9.70	4.95
Catchment area (km^2)	650	165	165
Volume (m^3)	93×10^6	25×10^6	1.23×10^6
Water level variation (m)	5.46	5.38	2.68

4.2.2 **Fisheries characteristics**

The targeted cichlid species represent 89%, 74%, and 71% of the catch (landed weight) composition at Tono, Bontanga, and Golinga reservoirs, respectively. The main fishing gears used are gillnets, cast nets, traps, and hook and lines. Typically, crews of one to three people use the gear from canoes (average length of 7 m) wading through the shallow regions. Fishers operate between 240-288 fishing days per annum. Over the course of the study we, we did not encounter any Fisheries Commission officers at Bontanga or Golinga. However, at Tono, a fisheries officer collects catch data on a monthly basis. The fisheries are managed by the riparian fishing communities and the management is headed by a chief fisher or/chairman. The chairman's task is to ensure that fisheries regulations and agreed bylaws are followed. A task force enforces the regulations at Tono. Surveys conducted between July 2016 and June 2017, recorded 417 active fishermen at Tono, while Bontanga and Golinga had 96 and 18 active fishermen, respectively.

4.2.3 **Catch and size frequency data collection**

Fish landings were observed and recorded for 5 consecutive days in each month and extrapolated to the monthly catch using an estimate of the average number of fishing days per month. Respective information was obtained from the fishers at the three reservoirs. The bulk weight of each fisher's catch per day was recorded and the caught fishes were then sorted into the target species, counted and weighed. At Tono, the 3 landing sites with the largest fisher populations (i.e., bays two, three, and four, Fig. 4.1) were monitored simultaneously for 3 days and bays one and five were monitored for the remaining 2 days. The two landing sites at Bontanga were monitored simultaneously during the study period while the single landing site at Golinga was only monitored from November 2016 to June 2017 as there was insignificant fishing during the preceding rainy season (July-October 2016).

Samples of the target fish species were collected from artisanal fishers from July 2016 to June 2017 at the Tono and Bontanga reservoirs and from November 2016 to June 2017 at the Golinga Reservoir. Fishers operate with gill nets of mesh sizes between 15 mm and 70 mm. The total lengths of the fish were measured to the nearest 0.1 cm using a fish measuring board. Each fish was then weighed with a digital weighing scale to the nearest 0.01g.

4.2.4 **Length frequency data correction**

Before the assessment steps, the length-frequency (LFQ) data collected was raised to the monthly catches for each target species assuming that the sample adequately represents the length distribution of the total catch for the month (Annex II, Table S4.1). The LFQ data were then corrected by taking into account the selectivity of the gear. For this purpose, data from the field studies were processed and analyzed for gillnet selectivity using Pasgear II (Kolding and Skaalevik, 2010). Details on the abundance of each species captured by gillnets of different mesh sizes at the 3 reservoirs are available in the Annex II, Table S4.2. Pasgear II computes selectivity parameters using the SELECT statistical model method (Millar, 1992; Millar and Fryer, 1999; Millar and Holst, 1997). Thereby, selectivity parameters are estimated indirectly from comparative data of observed catch frequencies across a series of mesh sizes using 5 different models (normal location, normal scale, log-normal, gamma, and bi- modal (Kolding and Skaalevik, 2010)). The model with the lowest deviance is selected as the best. To obtain the estimated (reconstructed) ‘true’ frequencies of the monthly catches, the observed LFQ were finally corrected using a combined probability of the fleet selection (for details see Annex II, Table S4.3).

4.2.5 **Assessment approach**

4.2.5.1 **The TropFishR package**

The R package TropFishR (Mildenberger et al., 2017) was used to assess the reservoir fisheries following the steps outlined in Sparre and Venema (1998). TropFishR includes enhanced versions of all the functions in FAO-ICLARM Stock Assessment Tools II (FISAT II) (Gayanilo et al., 2005) with some more recent methods added. The package has traditional and updated versions of the Electronical LEngth Frequency ANalysis (ELEFAN) method (Pauly, 1980), used in growth parameter estimation, with new optimization techniques (Taylor and Mildenberger, 2017), Millar's nonlinear selectivity models (Millar and Holst, 1997), and a complete set of methods for fisheries analysis with LFQ data. The package allows a stock assessment routine to derive reference levels (e.g. F_{MSY}, $F_{0.1}$) using yield per recruit modelling based on a single year of LFQ data (Mildenberger et al., 2017).

The individual steps of the length-based stock assessment outlined by Sparre and Venema (1998) and for TropFishR by Mildenberger et al. (2017) were implemented within a bootstrapping framework (Mildenberger et al., 2018; Mildenberger et al., 2017; Schwamborn et al., 2019). This allows one to estimate uncertainty intervals for all parameters and avoid the seed effect (Schwamborn et al., 2019). The framework applies the 5 subsequent steps listed below to each resampled LFQ data set.

4.2.5.2 **ELEFAN and growth parameters estimation**

ELEFAN is a method to estimate growth parameters of the von Bertalanffy growth function (VBGF) from the progression of LFQ modes through time (Pauly, 1980). It requires a vector with the mid-lengths of defined length classes, a matrix with catches in numbers per length class (rows) and per sampling time (columns), and a vector with the dates of the sampling times. The ELEFAN estimates the growth parameters following 3 steps: (i) 'restructuring' of LFQ data according to a procedure that scores length bins based on deviations from a moving average across neighboring bins, (ii) calculation of the cumulative score for a given set of VBGF parameters based on the bin scores that are intersected by resulting growth curves, and (iii) search for VBGF parameters that result in the maximum score value (Mildenberger et al., 2017). After the LFQ adjustments, a bootstrapped ELEFAN with genetic algorithm optimization function (bootstrapped ELEFAN_GA) (Mildenberger et al., 2018; Mildenberger et al., 2017; Schwamborn et al., 2019) was applied to the LFQ allowing to assess the uncertainties around the growth estimates. Total length measurements grouped into 1 cm class intervals were used to assess the growth parameters of the species using seasonally oscillating von Bertalanffy growth function (soVBGF) (Pauly and Gaschutz, 1979; Somers, 1988):

$$L_t = L_\infty\left(1 - e^{-(K(t-t_0)+S(t)-S(t_0))}\right), \tag{1}$$

where L_t is the total length of the fish at time t, L_∞ is the asymptotic length of fish in cm, K is the rate at which L_t approaches L_∞, and t_0 is the theoretical age of the fish when L_t is equal to zero. *S(t)*

$= (CK/2\pi) \sin 2\pi(t - t_s)$, C is a constant indicating the amplitude of the oscillation, typically ranging from 0 to 1 (a value >1 implies periods of shrinkage in length, which is rare), and t_s is the fraction of a year (relative to the age of recruitment, $t = 0$) where the sine wave oscillation begins (i.e., turns positive).

An initial seed value of L_∞ was based on $Lmax$, derived from the mean of the 1% largest fish in the sample and following the formula from Pauly (1984):

$$L_\infty = Lmax/0.95. \tag{2}$$

The VBGF parameters were assessed using a Moving Average (MA) over 5 size intervals. Since the VBGF parameters are known to be sensitive to the MA setting (Taylor and Mildenberger, 2017), the bootstrapped ELEFAN_ GA function was also rerun for each assessment with MA of 3 and 7 size intervals.

The estimated L_∞ and K values were used to calculate the growth performance index (Phi prime (φ′) defined by (Pauly and Munro, 1984) as:

$$\varphi' = \log K + 2\log L_\infty. \tag{3}$$

If the LFQ of the fish from the individual reservoirs resulted in poor fits of the growth curve to the data, the data of the individual reservoirs were pooled for each species, resulting in significantly improved data sets per species (combined LFQ). The aggregation of LFQ increases the sample size, which is of high importance for ELEFAN (Schwamborn et al., 2019). Growth parameters were then assessed for the combined data sets. The length-converted catch curves were conducted for each reservoir separately based on those growth parameters of the combined data sets. One additional output of the ELEFAN run in TropFishR is the parameter t_{anchor}, which represents the fraction of the year where yearly repeating growth curves cross length equal to zero.

4.2.5.3 **Mortality and exploitation rate**

The instantaneous rate of total mortality (Z) was estimated by the linearized length-converted catch curve method:

$$\log\left(\frac{N_i}{dt_i}\right) = \mathrm{a} + \mathrm{bt}, \tag{4}$$

where N_i is the number of individuals in length class I, d_{ti} is the time needed by the fish to grow in that class i (Pauly, 1990; Pauly et al., 1995), a is the intercept, b corresponds to -Z, and t is the relative age (age – t_0). The rate of natural mortality (M) was estimated using the empirical equation by Then et al. (2015):

$$M = 4.118K^{0.73}L_\infty{}^{-0.33}. \tag{5}$$

This approach is an update of Pauly's growth-based method (Pauly, 1980) of natural mortality estimation, recommended for data-poor situations. The method was used since the fisheries of the region is data-limited and no data on maximum age ($t_{\max}$) is available for the target species. It should be noted that this approach is based on meta-analysis with a cross-validation prediction error of 0.6. Consequently, the uncertainties around the estimates of the total and fishing mortalities are compounded by the error associated with the natural mortality estimate. Fishing mortality rate (F) was estimated based on the relationship:

$$\mathrm{F} = \mathrm{Z} - \mathrm{M}. \tag{6}$$

The exploitation rate (E) was determined by

$$E = \frac{F}{Z} \quad \text{(Gulland, 1971).} \tag{7}$$

Estimated values of E were then compared to a reference value of 0.5, which has been proposed as an upper level of sustainable exploitation for most fish species (Gulland, 1971). The estimated exploitation rates were derived from maximum density values of distributions for each parameter obtained from the linearized length-converted catch curve through the bootstrapping approach. While F and M add up to Z on the level of the resamples, the maximum density estimates (and medians) do not have to add up, as the maximum density of each distribution is determined independently from the other parameters. The fishing mortality rate (F) estimate was also compared to the fishing mortality value at Maximum Sustainable Yield (F_{MSY}), defined (Zhou et al., 2012) as:

$$F_{MSY} = 0.87M. \tag{8}$$

4.2.5.4 **Size at first capture**

The mean length (L_c) at which 50% of the fish are retained by the gear, was estimated from the individual observed catch frequencies of the different mesh sizes that are used to target species at each reservoir. The ogive selection routine of Pasgear II was used to estimate the Lc, assuming that the probability of capturing a fish is solely dependent on its length.

4.2.5.5 **Stock size estimates through cohort analysis**

The length-based virtual population analysis ((Jones, 1984) was conducted to reconstruct the standing biomass of the stocks of the target species and to estimate fishing mortality per length class using the L_∞ and K values from the bootstrapped ELEFAN_GA analysis. The annual mean value of F derived through the length converted catch curve was used as an estimate for the fishing mortality of the last length class (terminal F). The last length classes, with low catch numbers, were grouped into plus groups for each species. The length-based VPA is based on the following two equations:

$$N_{i+1} = N_i exp\big(-(F_i + M)\big) \text{ and } \tag{9}$$

$$C_i = N_i \frac{F_i\big(1-exp(-(F_i+M))\big)}{F_i+M}, \tag{10}$$

where N is the stock size in numbers, C is the catch, F is the fishing mortality, and M is the natural mortality. The biomasses of the different length classes were calculated with the length-weight relationship formula using the constant (*a*) and the exponent (*b*) values derived from the data of the study (Table 4.2).

4.2.5.6 **Relative yield per recruit (Y'/R) and reference points**

The model of Thompson and Bell (Thompson and Bell, 1934) which estimates yields, biomass, and value as a function of fishing effort (or fishing mortality) and gear selectivity parameters was used to predict: (a) the fishing mortality that produces the highest yield per recruit (F_{max}), (b) the fishing mortality that results in a 50% reduction of the biomass compared to the unexploited population ($F_{0.5}$), and (c) a fishing mortality which corresponds to 10% of the slope of the yield per recruit curve at the origin ($F_{0.1}$). This model builds on the output of the length-based VPA with the following input parameters: K (annual growth coefficient); ta (anchor point); L_∞ (asymptotic length); M (Natural mortality); a (constant of LWR); b (exponent of LWR); Lr (length at recruitment to fishery), L50 and L75 (selectivity parameters) (Sparre and Venema, 1998; Thompson and Bell, 1934). The 3 reference points, namely F_{max}, $F_{0.5}$, and $F_{0.1}$ with their confidence intervals were used to determine the exploitation status of the 3 stocks of Bontanga, Tono, and Golinga reservoirs.

Table 4.2. Summary statistics and length-weight relationships of the target fish species from Bontanga, Tono, and Golinga reservoirs of Northern Ghana.

Reservoir	Family	Species	N	TL (cm) range	*Lmean* (cm)	L_c (cm)	BW (g) range	*a* (Cl$_{95\%}a$)	*b* (Cl$_{95\%}b$)	r^2
Bontanga	Cichlidae	*Coptodon zillii* (Gervais 1848)	2393	5.6-24.0	9.2	7.2	1.1-274.3	0.0236 (0.0224-0.0248)	2.89 (2.86-2.91)	0.9598
	Cichlidae	*Oreochromis niloticus* (Linnaeus 1758)	2678	6.1-37.5	12.3	10.7	2.1-1190.3	0.0226 (0.0213-0.0240)	2.93 (2.91-2.95)	0.9567
	Cichlidae	*Sarotherondon galilaeus* (Linnaeus 1758)	2677	6.0-21.9	11.4	10.9	4.6-196.8	0.0210 (0.0199-0.0222)	2.97 (2.95-2.99)	0.9605
Tono	Cichlidae	*Coptodon zillii* (Gervais 1848)	2584	7.0-19.6	11.2	9.0	4.0-126.9	0.0155 (0.0145-0.0165)	3.04 (3.02-3.07)	0.9513
	Cichlidae	*Oreochromis niloticus* (Linnaeus 1758)	2638	9.2-24.7	15.2	13.4	13.5-243.9	0.0248 (0.0232-0.0265)	2.88 (2.86-2.91)	0.9537
	Cichlidae	*Sarotherondon galilaeus* (Linnaeus 1758)	2700	9.9-22.4	15.3	12.7	18.4-169.9	0.0275 (0.0255-0.0297)	2.84 (2.82-2.87)	0.9388
Golinga	Cichlidae	*Coptodon zillii* (Gervais 1848)	261	6.5-23.3	10.5	8.6	5.3-219.6	0.0141 (0.0121-0.0165)	3.10 (3.03-3.16)	0.9710
	Cichlidae	*Oreochromis niloticus* (Linnaeus 1758)	1157	6.4-26.7	13.5	12.1	5.1-381.8	0.0219 (0.0203-0.0236)	2.95 (2.92-2.98)	0.9718
	Cichlidae	*Sarotherondon galilaeus* (Linnaeus 1758)	971	5.8-21.2	12.4	11	1.3-196.5	0.0194 (0.0180-0.0210)	3.00 (2.97-3.03)	0.9745

N, sample size; *Lmean, mean length of catch*; L_c, length at first capture; TL, Total Length (cm, min–max); BW, Body Weight (g, min–max); a, intercept; b, slope; CI, confidence interval; r^2, determination coefficient.

4.2.5.7 **Length-based indicators for sustainable catches**

Froese (2004) proposed 3 length-based metrics indicative of sustainable fishing. These metrics form our second approach for the assessment of stock status, which are:

(a) Pmat: the proportion of mature fish in the catch, with 100% as the reference target point, based on the formula:

$\text{Pmat} = \%\ \text{fish in sample} > \text{Lm};$ (11)

where Lm is the length at first sexual maturity. The desirable target would be to let as many fish as possible spawn at least once before they are caught to rebuild and maintain healthy spawning stocks (Froese, 2004). The total length at first sexual maturity was based on published research on the species (Adite and Van Thielen, 1995; Akongyuure et al., 2017b; Duponchelle and Panfili, 1998; Kwarfo-Apegyah and Ofori-Danson, 2010; Lederoun et al., 2016; Ofori-Danson et al., 2008). The mean Lm values corresponded to 7.9 cm, 11.9 cm, and 11.3 cm for *C. zillii*, *O. niloticus*, and *S. galilaeus*, respectively.

(b) Popt: proportion of fish within a 10% range around the optimum length (Lopt) in the catch, with 100% as the reference target, based on the formula:

$\text{Popt} = \%\ \text{fish} > \text{Lopt} - 10\%\ \text{and}\ < \text{Lopt} + 10\%;$ (12)

where:

$\log(Lopt) = 1.053 * \log(\text{Lm}) - 0.0565$ (Froese and Binohlan, 2000). (13)

The *Lopt* for the target species based on the formula above were 7.7 cm, 11.9 cm, and 11.3 cm for *C. zillii*, *O. niloticus*, and *S. galilaeus*, respectively.

(c) Pmega: proportion of "mega-spawners" in the catch, with 30-40% as a desirable target reference point, based on the formula (Froese, 2004):

$\text{Pmega} = \%\text{fish} > \text{Lopt} + 10\%\ .$ (14)

The lengths (Lmega) for the Pmega calculation were 8.5, 13.1, and 12.40 cm for *C. zillii*. *O. niloticus,* and *S. galilaeus*, respectively.

Following a decision tree procedure by Cope and Punt (2009), the 3 proportions were summed (Pmat + Popt + Pmega) to obtain *Pobj*, an indicator of stock status above spawning biomass (SB) reference points. The Pobj allows for differentiation of selectivity patterns, as the authors observed that Pobj had a more consistent relationship with spawning biomass (SB) than any of the individual metrics (Pmat, Popt or Pmega) and that different selectivity patterns in the fishery were associated with a range of values of Pobj. Once a selectivity pattern is established based on Pobj, threshold values of Pmat, Pobj and/or the Lopt/Lm ratio point to an estimated probability of the stock spawning biomass (SB) being below established reference points, either 40% or 20% of the unfished spawning biomass (0.4SB or 0.2SB).

4.3 Results

Eighteen thousand and fifty-nine fish were measured consisting of 5,238 *C. zillii*, 6,473 *O. niloticus*, and 6,348 *S. galilaeus*. Monthly catch varied significantly among the species and the reservoirs. The lowest catch was at Golinga where no significant commercial catches were obtained from July 2016 to November 2016 (Table 4.3). Details on the size composition are available in Table 4.2 and Fig. 4.2.

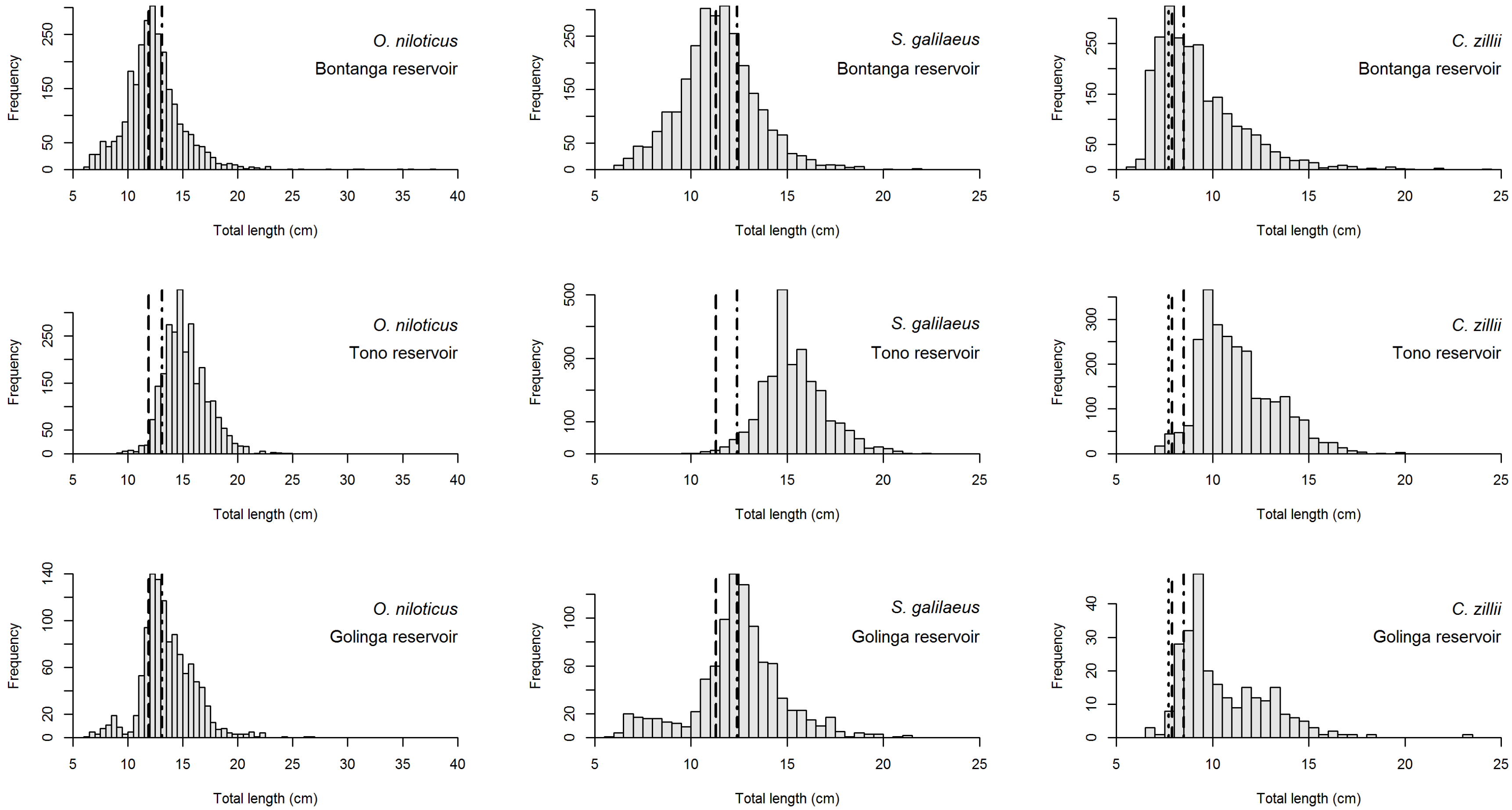


Figure 4.2. Size distribution of *O. niloticus*, *S. galilaeus*, and *C. zillii* landings observed from July 2016 to June 2017 at Bontanga, Tono, and Golinga reservoirs of Northern Ghana. The vertical lines represent the length based reference values: length at first maturity (dashed line), optimum length Lopt (dotted line), and starting length of mega-spawners (‘dot-dashed’ line).

Table 4.3. Catch (in tonnes) of *Coptodon zillii*, *Oreochromis niloticus*, and *Sarotherondon galilaeus* recorded through field survey at Tono, Bontanga, and Golinga reservoirs from July 2016 to June 2017.

Species/Reservoir	Tono	Bontanga	Golinga	Total
Coptodon zillii	12.36	9.72	0.14	22.22
Oreochromis niloticus	52.01	19.75	4.28	76.04
Sarotherondon galilaeus	103.06	48.9	3.13	155.09
Total	167.43	78.37	7.55	253.35

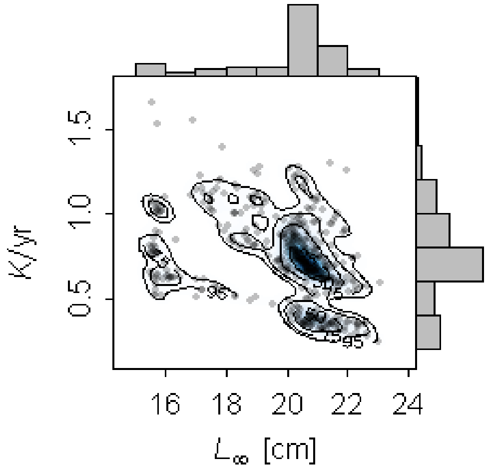
4.3.1 **Catch and gillnet selection correction**

For the 3 species, at all the reservoirs, the period coinciding with the dry season (January-June) had required a higher raising factor for the catch and gillnet selectivity correction than the raining season (Annex II, Table S4.1) due to reduced fishing activities as fishers add crop and vegetable production to their livelihood activities. The correction for gillnet selectivity was applied across the total length classes for the species based on the combined fleet selectivity available in Annex II, Table S4.3.

4.3.2 **Growth parameters**

The maximum density values after 500 resamples were closer to the upper limit of the respective confidence intervals. The maximum density estimates of *K* were similar between species: 0.71, 0.85, and 0.79/yr for *C. zillii*, *O. niloticus*, and *S. galilaeus*, respectively (Fig. 4.3). *Sarotherondon galilaeus* had the narrowest confidence intervals for L_∞ and *K,* while *O. niloticus* and *C. zillii* had the highest uncertainties for the L_∞ *and K* estimates, respectively (Table 4.4, Fig. 4.3). The growth performance index values were similar among the 3 species and were within 2.40 and 2.78. The maximum density estimates of the parameter t_{anchor} were 0.41, 0.52, and 0.64 representing the months of June, July, and September where yearly repeating growth curves cross length equal to zero for *C. zillii*, *O. niloticus*, and *S. galilaeus*, respectively. The results of the ELEFAN assessments using an MA of 3 and 7 size intervals are available in Annex II, Table S4.4.

Coptodon zillii

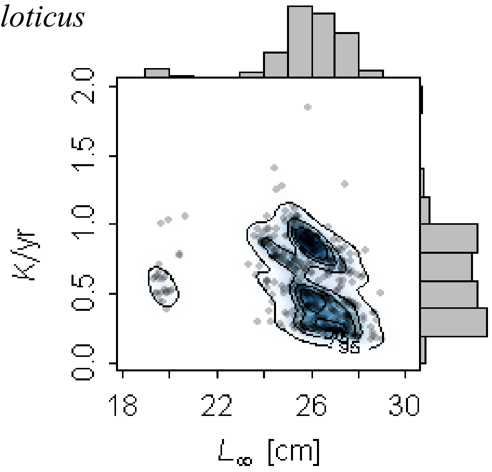


Maximum density

L∞: 20.60 cm

K: 0.71/yr

Oreochromis niloticus

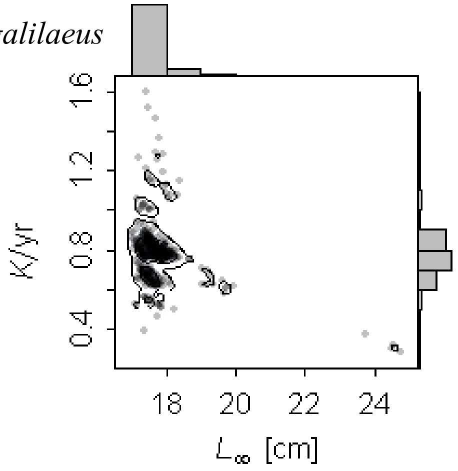


Maximum density

L∞: 25.92 cm

K: 0.85/yr

Sarotherodon galilaeus

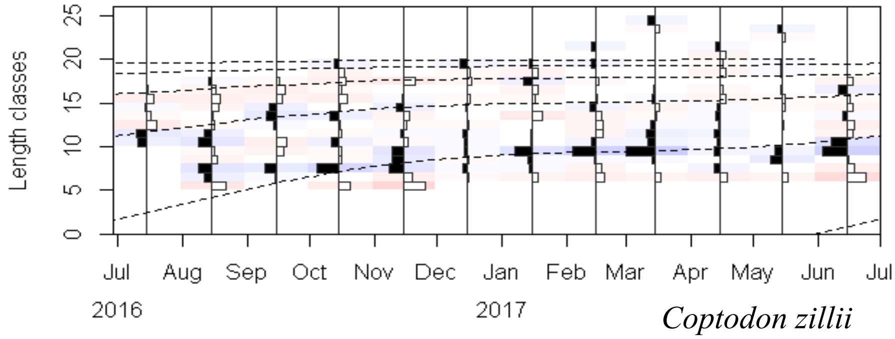


Maximum density

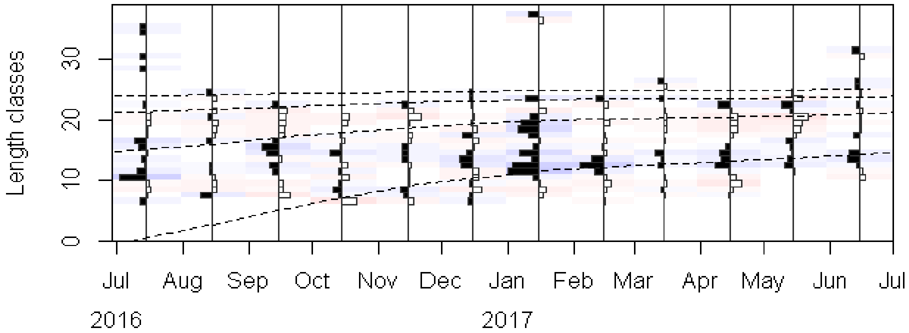
L∞: 17.79 cm

K: 0.79/yr

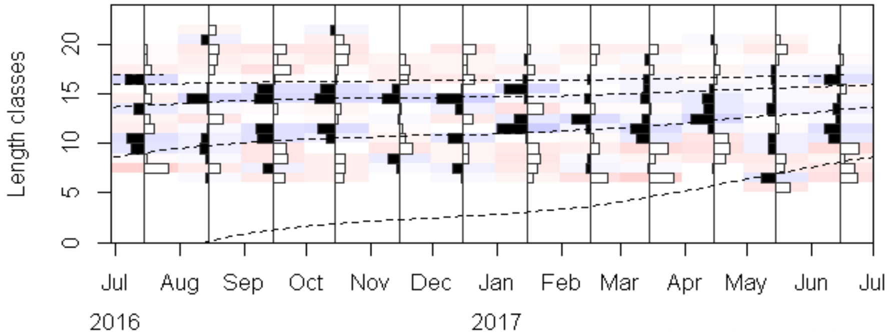
Figure 4.3. Scatter histogram of bootstrapped ELFFAN with genetic algorithm optimisation for the target species from 3 reservoirs using TropFishR. The points represent the individual combinations of L∞ and K estimates, while the contours represent the density of the combinations. The histograms represent the marginal distributions of the L∞ and K estimates, respectively.



Coptodon zillii



Oreochromis niloticus



Sarotherodon galilaeus

Figure 4.4. Length frequency histograms with the growth curves (dashed lines) obtained through the bootstrapped ELEFAN with GA analysis superimposed for *Coptodon zillii*, *Oreochromis niloticus*, and *Sarotherodon galilaeus*. The bars represent the restructured length frequency data, where black bars indicate positive peaks and white bars represent negative peaks. The method tries to maximize the number of positive peaks hit. The faint blue and red colors emphasize positive and negative peaks, respectively.

Table 4.4. Parameter estimates (mode of marginal distribution-Mod) of the seasonally oscillating von Bertalanffy growth function of the target fish species from reservoirs assessed with the bootstrapped electronic length frequency analysis with genetic algorithm function of TropFishR. Estimates based on the pooled length-frequency data of Tono, Bontanga, and Golinga reservoirs collected from July 2016 to June 2017. Lower and upper denote 95% confidence interval of the estimates.

Species	Parameter	Mod	Lower	Upper
C. zillii	L_∞ (cm)	20.60	15.62	22.34
	K (yr^{-1})	0.71	0.33	1.22
	t_{anchor}	0.41	0.19	0.87
	C	0.76	0.21	0.94
	Ts	0.64	0.24	0.79
	Φ	2.48	1.91	2.79
O. niloticus	L_∞ (cm)	25.92	19.80	28.23
	K (yr^{-1})	0.85	0.21	1.05
	t_{anchor}	0.52	0.17	0.87
	C	0.52	0.16	0.92
	Ts	0.74	0.11	0.94
	Φ	2.76	1.91	2.92
S. galilaeus	L_∞ (cm)	17.79	17.16	19.10
	K (yr^{-1})	0.79	0.52	1.15
	t_{anchor}	0.61	0.21	0.79
	C	0.70	0.30	0.90
	Ts	0.41	0.23	0.70
	Φ	2.40	2.19	2.62

4.3.3 **Mortality and exploitation rate estimates**

Estimates of total mortality were computed by applying the growth parameters of the pooled data assessed with MA of 5 to the individual LFQ data of the species. It should be noted that the natural mortality (M) value was assumed to be the same for a species across the reservoirs. Total and fishing mortalities, however, differed among the species and the reservoirs. The estimated exploitation rates for the different species in the 3 reservoirs ranged from 0.23-0.66/yr with confidence intervals within the range of 0.31-0.77/yr (Table 4.5, Figure 4.5). The maximum density values and confidence intervals of the exploitation rate of *C. zillii* stock at Bontanga and *S. galilaeus* at Golinga were below the optimal exploitation rate ($E_{0.5}$). *Oreochromis niloticus* stock at Tono Reservoir had maximum density and confidence interval values above the optimal exploitation rate ($E_{0.5}$). The rest of the stocks had maximum density and confidence intervals spanning between underexploitation and overexploitation. The length-frequency data of *S. galilaeus* stock in the Tono Reservoir did not allow for the running of linearized length-converted catch curve with the growth parameters from the ELEFAN with an MA equal to 5. However, the results on the exploitation of this stock assessed with an MA of 3 is presented in Annex II, Table 5a. The results indicate that most of the data points selected for the estimation of *Z* value for *S. galilaeus* and *C. zillii* after 500 resample were within the confidence limits, while *O. niloticus* had a wider distribution of data points (Figure 4.5).

Table 4.5. Estimated mortality values (Z, M, and F), exploitation rate (E), and biological reference points of fishing mortality (FMSY, Fmax, F0.1, F0.5) for the target species of Tono, Bontanga, and Golinga reservoirs. Mod: mode of the marginal distribution. Low (lower) and Upp (upper) denote 95% confidence interval of the estimates. Estimates are based on the pooled growth parameters with moving average of 5, hence the M estimate of a species is a common value for all reservoirs.

Species	Parameter (yr^{-1})	**Bontanga**			**Tono**			**Golinga**		
		Mod	Low	Upp	Mod	Low	Upp	Mod	Low	Upp
C. zillii	Z	2.16	1.06	3.53	1.94	1.69	5.84	2.37	1.30	4.06
	M	1.17	0.66	1.80	1.17	0.66	1.80	1.17	0.66	1.80
	F_{MSY}	1.02	0.57	1.57	1.02	0.57	1.57	1.02	0.57	1.57
	F	0.94	0.35	1.84	1.29	0.61	4.48	1.17	0.40	2.46
	E	0.43	0.33	0.52	0.66	0.36	0.77	0.49	0.31	0.61
	F0.1	0.93	0.76	1.85	1.17	0.56	1.79	1.15	0.63	1.81
	Fmax	6.97	1.91	7.00	2.50	1.22	7.00	2.19	1.73	7.00
	F0.5	0.57	0.49	1.42	0.85	0.42	1.52	0.83	0.42	1.33
O. niloticus	Z	1.88	1.04	4.28	1.74	0.97	4.48	3.54	1.05	5.18
	M	1.25	0.43	1.48	1.25	0.43	1.48	1.25	0.43	1.48
	F_{MSY}	1.09	0.37	1.29	1.09	0.37	1.29	1.09	0.37	1.29
	F	1.15	0.51	3.02	0.96	0.49	3.08	0.81	0.61	3.73
	E	0.61	0.49	0.71	0.55	0.50	0.69	0.23	0.58	0.72
	F0.1	1.02	0.82	2.78	1.89	1.05	3.54	1.79	0.66	2.17
	Fmax	4.16	1.80	7.00	6.97	3.59	7.00	6.99	1.89	7.00
	F0.5	1.50	0.49	1.76	1.67	0.95	3.19	1.21	0.43	1.65
S. galilaeus	Z	2.64	1.48	3.64				2.03	1.82	3.36
	M	1.32	1.00	1.77				1.32	1.00	1.77
	F_{MSY}	1.15	0.87	1.54				1.15	0.87	1.54
	F	1.34	0.46	2.05				0.91	0.70	1.66
	E	0.51	0.31	0.56				0.45	0.38	0.49
	F0.1	1.54	0.68	5.06				1.72	1.48	4.40
	Fmax	4.92	1.65	7.00					7.00	7.00
	F0.5	1.26	0.51	2.07				1.68	1.61	2.83

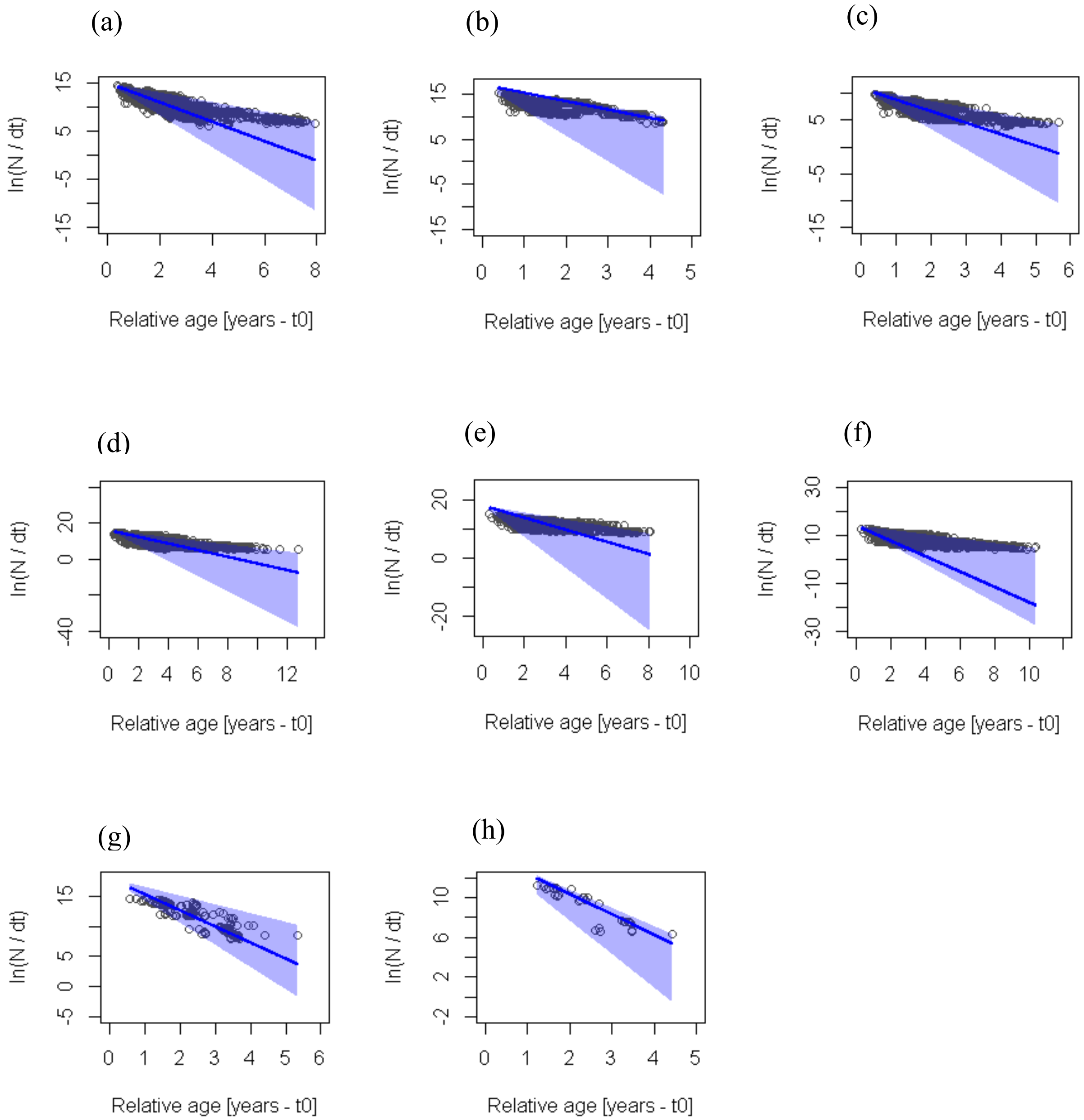


Figure 4.5. Bootstrapped linearized length-converted catch curve based on one-year catch data with selectivity correction. (a) *C. zillii*-Bontanga, (b) *C. zillii*-Tono, (c) *C. zillii*-Golinga, (d) *O. niloticus*-Bontanga, (e) *O. niloticus*-Tono, (f) *O. niloticus*-Golinga, (g) *S. galilaeus*-Bontanga, and (h) *S. galilaeus*-Golinga. The circles represent the points of the catch curve, which was applied to each resampled data set. The line represents the regression line corresponding to the maximum density estimates of the 500 estimated catch curves. The blue shaded area represents the 95% confidence interval for the maximum density regression line.

4.3.4 Size at first capture

The mean length (L_c) at first capture varied among the species and the reservoirs. *C. zillii* had the lowest L_c values while those of *O. niloticus* and *S. galilaeu*s were higher. Bontanga had the lowest L_c values, whereas Tono Reservoir had the highest L_c values for the 3 target species (Table 4.2).

4.3.5 Stock size estimates by cohort analysis

Coptodon zillii had the lowest biomass per unit of area in all the 3 reservoirs with 3.08, 0.87, and 0.45 tonnes/km^2 at Bontanga, Tono, and Golinga, respectively. *Oreochromis niloticus* biomass at Bontanga, Tono and Golinga were 6.19, 6.03, and 13.05 tonnes/km^2, respectively, while *S. galilaeus* had the highest biomass per unit of area in all the 3 reservoirs with 10.66, 9.33, and 16.52 tonnes/km^2 at Bontanga, Tono, and Golinga, respectively. Overall, the 3 cichlid stocks combined had a biomass of 30.02 tonnes/km^2 at Golinga, 19.93 tonnes/km^2 at Bontanga, and 16.23 tonnes/km^2 at Tono (Table 4.6).

Table 4.6. Biomass (in tonnes) of *Coptodon zillii*, *Oreochromis niloticus*, and *Sarotherondon galilaeus* estimated using Jones' cohort analysis.

Species/Reservoir	Tono		Bontanga		Golinga	
	Biomass (t)	Productivity (t/km^2)	Biomass (t)	Productivity (t/km^2)	Biomass (t)	Productivity (t/km^2)
C. zillii	16.24	0.87	20.61	3.08	0.28	0.45
O. niloticus	112.17	6.03	41.50	6.19	8.09	13.05
S. galilaeus	173.63	9.33	71.44	10.66	10.23	16.52
Total	302.04	16.23	133.55	19.93	18.60	30.02

4.3.6 Yield per recruit reference points

The estimated current fishing mortality values of the stocks are lower than the F_{max} values predicted to give maximum relative yield per recruit, but were close to the $F_{0.5}$ values (Table 4.5; Annex II, Table S4.5), indicating that the current fishing mortality maintains 50% of the biomass of the stock and the stocks are not overexploited but rather fully exploited. Comparing *F0.1* to *F* indicates that the current fishing mortality rates of *S. galilaeus* in Bontanga and Golinga, and those of *O. niloticus* in Tono and Golinga are below the rates at which the marginal yield per recruit is only 10% of the marginal yield-per-recruit of the unexploited stock. Although the 3 species showed slight differences in the *Fmax* values, the estimates for *O. niloticus* were similar across the 3 reservoirs. Similarly, the *F0.5* values were close among the species and the reservoirs (Table 4.5).

4.3.7 **Length-based indicators (LBI)**

The length-based indicators show that the cichlid stocks at the Tono Reservoir have spawning biomasses above 0.4, which is the unfished biomass reference point. The cichlid stocks spawning biomasses at Bontanga were all below 0.4. The LBI analysis suggests that at Golinga only *Coptodon zillii* has spawning biomass above the reference biomass of 0.4 times the unfished biomass. The length distribution of the fish caught at the reservoirs (Table 4.6, Fig.4.3) indicates that the 3 stocks at Tono had landings with 98% of the fish having a probability of being sexually mature of 50% (regarding the length at first sexual maturity). The landings at Bontanga had between 55-66% of fish being above the length at first sexual maturity while the proportion of the landings at Golinga that had fish above the length at first sexual maturity spanned between 80-95%. Tono and Bontanga had the highest and the lowest *Pmega* values respectively for all the species. *Pmat* values followed the same order. Golinga had the highest *Popt* values for *O. niloticus* and *S. galilaeus* while Bontanga had the highest *Popt* value for *C.zillii*. The lowest *Popt* values for all the species were at Tono (Table 4.7).

Table 4.7. Proportions of mature fish (Pmat), optimum-sized fish (Popt), larger than optimum size fish (Pmega), and Pobj (= Pmat + Popt + Pmega) for each species, and from the 3 reservoirs based on the indicators proposed by Froese (2004) and the formulas described in the Methods. Stock condition interpretation is based on a decision tree proposed by Cope and Punt (2009), aimed to assess whether spawning biomass (SB) is above (>) or below (<) a reference point (RP) of 0.4 unfished biomass. The last column indicates the estimated probability of SB being lower than 0.4 of unfished biomass based on the same authors.

Species	Reservoir	*Pmat*	*Popt*	*Pmega*	*Pobj*	Stock condition interpretation	Probability
C. zillii	Bontanga	0.66	0.25	0.66	1.57	SB < RP	100%
	Tono	0.98	0.02	0.98	1.98	SB ≥ RP	0%
	Golinga	0.95	0.03	0.95	1.94	SB ≥ RP	0%
O. niloticus	Bontanga	0.55	0.40	0.34	1.29	SB < RP	100%
	Tono	0.98	0.10	0.90	1.97	SB ≥ RP	0%
	Golinga	0.80	0.37	0.56	1.73	SB < RP	100%
S. galilaeus	Bontanga	0.58	0.42	0.36	1.37	SB < RP	100%
	Tono	1.00	0.01	0.98	1.98	SB ≥ RP	0%
	Golinga	0.81	0.24	0.65	1.70	SB < RP	100%

4.4 Discussion

4.4.1 Length frequency analysis using TropFishR

Inland fish stocks in the tropics are largely assessed with length-based methods since other approaches (such as otolith techniques) are more difficult and costly to use. However, in Northern Ghana, length-frequency data are not available from the fisheries authorities. This research, therefore, was conducted to obtain data for length-based assessments. We assumed that target fish stocks in systems with similar ecological characteristics but different fishing pressure may be effectively assessed by (1) pooling the individual length-frequency data of the studied reservoir systems for deriving common growth parameters and then (2) analyzing the fisheries exploitation and stock sizes for each reservoir system using individual system length-frequency data. Additionally, through the correction of the length-frequency data for gear selection and raising it to represent the total catch of the system over the study period, we achieved more robust and stable estimates of mortality. When length-frequency data is available without any information on gear selection, a study on gear selectivity of the same or related species from a similar system with detail information on gear and mesh sizes can be used to either estimate or assume the selectivity curve of the interested system. The gillnet selectivity of this study can thus be applied to the species in other reservoir systems of the region where no selectivity studies have been carried out.

4.4.2 **Growth parameter estimates**

The growth parameters obtained in our study for *O. niloticus* resemble those of populations studied in the reservoirs of Burkina Faso reported by Baijot and Moreau (1997). For *S. galilaeus* our estimated asymptotic length (L_∞=17.8 cm) is within what has been reported for this species in other reservoirs of West Africa and our L_∞ and K estimates resemble those reported by Baijot and Moreau (1997) for populations in Loumbila and Ramitenga reservoirs in Burkina Faso. The similarity in the growth pattern of these two species can be attributed to the similar climatic conditions between Burkina Faso and the Northern sector of Ghana. However, studies on the same species in Doukon and Togbadji reservoirs in Benin by Lederoun et al. (2016) depict a larger asymptotic length, while the K estimates are comparable to those reported in this study (Table 4.8). The growth parameters of the target species estimated in our study are also similar and comparable to those reported for *C. zillii* and *O. niloticus* in a previous study of the Bontanga Reservoir by Ofori-Danson et al. (2008) but differ for *S. galilaeus.* The difference in the case of *S. galilaeus* could be as a result of a more precise estimation of the growth parameters in our study due to methodological improvements from the previous study. The growth of *C. zillii* has not been extensively studied in West Africa. A study on Sourou Reservoir by Baijot and Moreau (1997) reported slightly larger L_∞ and K values compared to our estimated values.

Table 4.8. Growth, mortality estimates, and exploitation rates from different fishing areas in West Africa including the estimates of the present study.

Species	L_∞ (cm)	K (/yr^{-})	Φ	Z (/yr^{-})	M (/yr^{-})	F (/yr^{-})	E (/yr)	Country	Locality	Reference
C. zillii	27.83	0.46		3.16	1.14	2.02	0.64	Nigeria	Cross River basin	(Uneke and Nwani, 2014)
	34	0.20	2.36					Burkina Faso	Sourou Reservoir	(Baijot and Moreau, 1997)
	21.9	0.6	2.46					Niger	River Niger	(Mérona, 1983)
	21.53	0.6	0.44	1.99	1.41	0.58	0.29	Ghana	Bontanga Reservoir	(Ofori-Danson et al., 2008)
	20.6	0.71	2.48	2.02	1.17	0.85	0.42	Ghana	Bontanga Reservoir	This study
	20.6	0.71	2.48	1.85	1.17	1.23	0.66	Ghana	Tono Reservoir	This study
	20.6	0.71	2.48	2.16	1.17	0.97	0.45	Ghana	Golinga Reservoir	This study
O. niloticus	26.2	0.7	2.68					Burkina Faso	Kokologho Reservoir	(Baijot and Moreau, 1997)
	23.7	0.29	2.21					Burkina Faso	Boulmigou Reservoir	(Baijot and Moreau, 1997)
	21.3	0.52	2.37					Burkina Faso	Petit Balé Reservoir	(Baijot and Moreau, 1997)
	15.8	0.75	2.27					Burkina Faso	Sourou Reservoir	(Baijot and Moreau, 1997)
	23.63	0.58	2.55	1.9	1.35	0.55	0.29	Ghana	Bontanga Reservoir	(Ofori-Danson et al., 2008)
	25.9	0.85	2.76	1.84	1.25	1.12	0.61	Ghana	Bontanga Reservoir	This study
	25.9	0.85	2.76	2.1	1.25	1.29	0.61	Ghana	Tono Reservoir	This study
	25.9	0.85	2.76	3.19	1.25	0.57	0.18	Ghana	Golinga Reservoir	This study
S. galilaeus	14.7	1.11	2.38					Burkina Faso	Loumbila Reservoir	(Baijot and Moreau, 1997)
	17.4	0.45	2.13					Burkina Faso	Ramitenga Reservoir	(Baijot and Moreau, 1997)
	26.2	0.73	2.70	1.76	1.51	0.27	0.15	Benin	Lake Doukon	(Lederoun et al., 2016)
	23.6	0.87	2.68	2.21	1.74	0.47	0.21	Benin	Lake Togbadji	(Lederoun et al., 2016)
	36.8	0.26	2.55	1.36	0.7	0.66	0.48	Ghana	Bontanga Reservoir	(Ofori-Danson et al., 2008)
	17.8	0.79	2.4	2.66	1.32	1.36	0.51	Ghana	Bontanga Rreservoir	This study
	17.8	0.79	2.4		1.32			Ghana	Tono Reservoir	This study
	17.8	0.79	2.4	2.05	1.32	0.93	0.45	Ghana	Golinga Reservoir	This study

4.4.3 **Fisheries exploitation**

While the use of different MAs and bin size revealed differences in the levels of uncertainty associated with growth and mortality parameters and stock conditions, the estimated qualitative exploitation rate (i.e., underexploited, optimal or overexploited) was not sensitive to these differences for six out of the eight assessments that were conducted using the three MA settings. The bootstrapped linearized length-converted catch curve approach depicts that stocks assessed as underexploited or overexploited (considering the highest density of the estimated exploitation rate) may have confidence limits that are entirely within the limits of under exploitation ($E \leq 0.5$) or overexploitation ($E \geq 0.5$) or have the lower limit as underexploited and the upper limit in the range of overexploitation. The stocks of *C. zillii* at the Bontanga and Golinga reservoirs both had estimated exploitation rates below 0.5 but the uncertainty around the estimate was far larger for Golinga than for Bontanga. Knowledge of the uncertainty of parameter estimates reflects the uncertainty in the data and can inform data monitoring (e.g., if available data is sufficient and which length classes are under-represented). Furthermore, the uncertainties can inform managers about the applicability and suitability of certain assessment methods and can be used when comparing results from different assessment approaches. Most importantly, the parameter uncertainties can be used in the definition of stochastic harvest control rules (e.g., in defining a harvest control rule which allows a 5% probability of the stock falling below a biomass reference point).

The assessment of the 3 target species in Bontanga by Ofori-Danson et al. (2008) indicated that these species were underexploited, whereas our study suggests that *C. zillii* and *S. galilaeus* are under optimal exploitation, and *O. niloticus* is overexploited. The shift from under- to over-exploitation for this species is likely due to the increase in the number of active fishers from 61 in 2009 (Alhassan et al., 2014) to the current fisher population of 96. At Tono, the largest reservoir in Northern Ghana and under great fishing pressure, our work is the first to provide information on the state of the exploited resources. While we recorded 417 active fishermen during our study, Akongyuure et al. (2017a) estimated the total number of fishers operating on the reservoir as 950. This could help explain the very high exploitation rates obtained for the target species in this reservoir.

In the Golinga Reservoir, the cichlid resources appear to be underexploited presumably because this reservoir is left unexploited for a quarter of the year due to the comparative advantage of crop production that the Golinga fishers engage in during the main farming season from July to October. A full year exploitation cycle will likely cause an increase in exploitation rates for all the species in the future. It is expected that any revamping (e.g. desilting and expansion of reservoir surface area) of the reservoir would accelerate fishing activities and may require access regulation to maintain the sustainable exploitation of the resources.

Overall, the parameters of the assessment reveal that the stocks are optimally exploited and the proportions of fish targeted seem adequate for the reservoirs fisheries sustainability. However, the present level of full exploitation of the target resources indicates no scope for further development and effort increase of the fisheries. The fishery at Tono Reservoir is driven by market preferences. Large-sized *Oreochromis niloticus*, which are mostly spawners are substantially targeted. If the current exploitation rate of 0.55/yr is not reduced, recruitment overfishing may prevail in the future. To prevent an increase in fishing effort, access rights to the fishery at Tono, Bontanga and Golinga reservoirs need to be formalized and regulated by Kassena Nankana Municipal Assembly, Kumbungu, and Tolon District Assemblies, respectively. Fishing community leaders and fisher groups should be involved in this process.

4.4.4 **Length based indicators**

Commercial fishing leads to changes in the size composition of the fished populations, so that simple length indicators of the fished population may be used to estimate the degree of exploitation (Arlinghaus et al., 2008; de Castro et al., 2015; Froese, 2004; Miranda and Dorr, 2000). Length compositions of caught fish should demonstrate the conservation of large, mature individuals (Berkeley et al., 2004). The LBI depicting that the spawning biomass of the stocks at Tono is above reference point is in contradiction to the exploitation rates obtained for *C. zillii* and *O. niloticus* based on the linearized length-converted catch curve analysis. The high *Pmega* values for the stocks at Tono indicate that a large fraction of mature individuals/mega spawners are available in the reservoir and confirms the market-driven size-selective fishery ongoing at the reservoir. Considering the high *Pmega* values, the overexploitation of the *C. zillii* and *O. niloticus* stocks in Tono Reservoir may trigger recruitment overfishing, if a less selective fishing pattern is not adopted. Less selective fishing patterns have been observed to preserve the relative proportion of the components in the fish community. This phenomenon has been achieved in several high-yielding small-scale inland fisheries in Africa by largely maintaining a balanced reduction of all species and size groups (Kolding et al., 2014; Kolding et al., 2015; Kolding et al., 2003; Kolding and van Zwieten, 2011; Misund et al., 2002). The results of the exploitation pattern at Tono, thus, call for a reconsideration of size-based regulations for the management of the reservoir fisheries. On the contrary, the size distribution of catches at the Bontanga Reservoir shows intensive exploitation of immature or small-sized fish. The retention of immature fish by gillnets at Bontanga is also evident from the low estimates of L_c for all the 3 species. This supports a previous study by Kwarfo-Apegyah and Ofori-Danson (2010) that revealed that the target resources at Bontanga Reservoir had small sizes with total length at first maturity corresponding to 11.8 cm, 9.3 cm and 5.9 cm for *O. niloticus, S. galilaeus*, *and C. zillii*, respectively.

Before the creation and enforcement of gear and mesh size regulations, the management of reservoir fishery resources should consider funding monitoring projects to obtain essential information about the fisheries through relatively simple and less costly stock assessment approaches. For example, the estimation of biological reference points and length-based indicators from routinely collected length-frequency and gear selectivity data. This is because restrictions that are not based on the knowledge of a fishery are likely to be ineffective in managing it. We suggest that the Fisheries Commission of Ghana should consider collaborating with the universities to conduct joint sample-based surveys at least biennially. This will help to assess changes in stock and update management strategies.

4.4.5 **Stock size**

The high productivity of the resources in the smallest reservoir (Golinga) is consistent with studies that indicate shallow and smaller African lakes are the most productive and that fish productivity generally declines with increasing lake size (Downing, 2010; Fernando and Holčík, 1982). The study on Bagré Reservoir in Burkina Faso by (Villanueva et al., 2006) reported biomasses of 5.12, 3.11 and 0.81 tonnes/km^2 for *S. galilaeus*, *O. niloticus*, and *C. zillii*, respectively, which are comparable to the biomasses of the species estimated in Tono Reservoir. The higher biomass of *C. zillii* at Bontanga compared to Tono, Golinga, and Bagré reservoirs are most likely attributable to the low exploitation of the species over time. Similarly, the relatively high biomass of *O. niloticus* at Golinga also reflects the current exploitation rate (0.23/yr) of the species could be increased if fishing continues to be seasonal. The biomasses of *S. galilaeus* populations at Bontanga and Golinga are higher than in the much larger Tono and Bagré reservoirs, which could be due to the species preference for small, shallow, and highly productive systems.

4.4.6 **Conclusions**

The use of two approaches in assessing the resources of the reservoirs offers a broader understanding of the status of the fisheries exploitation and their sustainability. Bootstrapped length-frequency analysis with TropFishR provided a holistic and robust assessment of the fisheries with sequential estimation of growth, mortality, exploitation rates, stock size parameters, and biological reference points, with associated uncertainties.

The length based-indicator approach allowed us to make a rapid and relatively simple decision on the sustainability of the fisheries based on spawning biomass reference point. The LBI provides an indirect assessment of fishing impact and the effect of gear selection on stock size composition. It has been noted that the cost, complexity, and the lack of technical capacity in many countries have made the scientific assessment and sustainable management of data-poor fisheries a persistent problem (Prince and Hordyk, 2018). This is particularly the case for reservoir fisheries in many tropical countries. Although the BFSA approach is robust and can pass as the best assessment framework for the determination of management reference points for reservoir exploited stocks, in extremely data-poor fisheries, where personnel are limited, the LBI method can provide limited preliminary assessment of the fisheries sustainability.

Our findings suggest that the target resources of Golinga are optimally exploited, likely due to the fact that fishing activities are limited to only 8 mo of the year. While the length-frequency assessment shows no indication of overexploitation of the fishery resources at Bontanga, fishing pressure on immature *C. zillii* population is high and may become critical if it is increased, since the current L_c is below the length at first maturity and is also below the lower limit of the *Lopt* range. Therefore, managing this stock will require that fishers at Bontanga agree to create bylaws that provide size control measures (e.g., restrictions on fishing on nursery grounds) to reduce immature proportions of current landings. The fishing pressure on large-sized *C. zillii* and *O. niloticus* populations at Tono Reservoir should be reduced to avert recruitment overfishing. Fisheries at Golinga can be sustainably exploited with the prevailing fishing pressure and pattern, which depict underexploitation of the fisheries resources. Further research to generate adequate data and knowledge on size composition of fish landings from major reservoirs, gear selectivity, and sizes at first sexual maturity of commercially important species is recommended to improve assessment and thus management advice of reservoir fisheries resources in Ghana.

CHAPTER 5: Feeding niche, growth characteristics and exploitation level of *Auchenoglanis occidentalis*

Comparing feeding niche, growth characteristics and exploitation level of the Giraffe catfish *Auchenoglanis occidentalis* (Valenciennes, 1775) in the two largest man-made lakes of northern Ghana

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Abstract

The stomach contents of the giraffe catfish, *Auchenoglanis occidentalis*, populations from Lake Bontanga and Lake Tono, two artificial lakes, were analysed, together with length frequency data collected from July 2016 to June 2017, to gain knowledge of the stock bioecology and exploitation status. The feeding characteristics of the giraffe catfish did not differ significantly between the lakes, as revealed by a Wilcoxon rank-sum test ($p > 0.05$). Insect larvae and algae dominated stomach content, with proportionate contributions of 43.8% and 14.2% in Lake Bontanga and 49.3% and 10.6% in Lake Tono, respectively. In the larger Lake Tono, the growth coefficient ($K = 0.34$ year) and asymptotic length ($L_\infty = 38.3$ cm) were higher than in Lake Bontanga and the exploitation rate was comparatively low ($E = 0.24$). This lower exploitation level in Lake Tono agrees with a higher mean catch size of 27.6 cm and a high spawning stock biomass >0.4 of the unfished biomass, as well as a stock biomass of 3.12 tonnes km^{-2}, suggesting that there is scope for an intensification of the fishery. In the smaller Lake Bontanga, the species growth was lower ($K = 0.31$ yr^{-1} and $L_\infty = 28.9$ cm) and the stock is fully exploited ($E = 0.48$). The mean catch size and spawning stock biomass were critically low; 17.2 cm and <0.4 of the unfished biomass, respectively. Accordingly, this stock requires close monitoring to prevent resource depletion

Keywords: bioecology, exploitation status, growth rates, length-based indicators, Lake Bontanga, Lake Tono, spawning stock biomass, stomach contents

5.1 Introduction

The study of fish diet based on an analysis of stomach contents is a standard practice in fish ecology (Hyslop, 1980) and it allows one to classify fish with respect to their feeding behaviour and trophic role (Boyd, 2002). Knowledge of the food spectrum, growth, mortality and stock biomass of fish groups are important for the construction of trophic models for ecosystem-based fisheries management. Notwithstanding, the diet composition of most fish species in the lakes and reservoirs of West Africa is poorly documented. The giraffe catfish *Auchenoglanis occidentalis* has commercial importance and is found in most lakes and rivers of West Africa (FishBase, 2019). In Ghana, Quarcoopome et al. (2008) reported that in terms of weight, *Auchenoglanis occidentalis* constituted 13.4% and 5.3% of the fishery harvests in Lake Bontanga and Lake Libga, respectively. Notwithstanding its importance, very limited research has been dedicated to the biology of this species. No information is available on the range of food items available to *A. occidentalis* in the artificial lakes of Ghana (FishBase, 2019).

Fish from freshwater systems in northern Ghana play an important role in small-scale fisheries, providing livelihoods to rural communities. This also holds for fisheries in artificial lakes that have yet received only limited scientific assessment in Ghana. Current threats to these waterbodies include environmental degradation, unpredictable changes in water levels and the widely unregulated exploitation of fish stocks. Inland fisheries, including those of artificial lakes, are accorded less importance relative to other uses of water (Welcomme et al., 2010). This results in poorly constrained estimates of the status of stocks and trends in catches, as well as difficulties in estimating their total production, and also their economic and societal values (FAO, 2009b).

The giraffe catfish *Auchenoglanis occidentalis* belongs to the family Claroteidae, which became separated from the family Bagridae based on genomic analysis, and reflect a monophyletic group of African catfish (Berra, 2001). The Claroteidae family in the freshwaters of Ghana is comprised of three genera, namely: *Chrysichthys*, *Clarotes* and *Auchenoglanis*, as well as seven species (Dankwa et al., 1999). Fish of this family are characterised by the presence of two to four pairs of barbels, well-developed pectoral-fin spines, a moderately or strongly developed adipose fin and a medium-sized anal fin. The mouth is supported dorsally by the premaxilla and part of the maxilla (Risch, 1985). The species are reported to reach up to 70 cm in length and a weight of 4.5 kg and its flesh is considered of a fair quality (FishBase, 2019; Reed, 1967). *Auchenoglanis occidentalis* is mainly omnivorous and an adaptive generalist feeder, with strong insectivorous tendency (Ouéda et al., 2008; Paugy and Lévêque, 1999). However, its feeding habit and food ingestion rate can greatly vary in tandem with the *in situ* food availability, which could differ between waterbodies.

The current study aimed at a comparison of the feeding niche and ecological role of the giraffe catfish and its exploitation level in two artificial lakes, which differ in size, mean depth, water level fluctuation and water volume capacity. Lake Tono is a large lake formed by two water sources. It has dense aquatic vegetation in the littoral zones, which become inundated during the rainy season. Lake Tono has larger deep zone areas than Lake Bontanga. There are also five small islands visible at low water levels. Because the giraffe catfish is known to occur in both lacustrine and riverine systems (Palomares et al., 2003), the population at Lake Tono is expected to have more diverse sources of food, and based on the aforementioned differences in environmental characteristics, we hypothesise that the giraffe catfish population in Lake Tono feeds more on plant material and associated insects than their counterparts in Lake Bontanga do and that growth conditions might well be more favourable in Lake Tono.

The objectives of the study were accordingly to provide information on: (i) the food items ingested by the species and their relative abundance in the two lakes; (ii) the von Bertalanffy growth parameters (asymptotic length and growth coefficient) of the species; (iii) the population size (absolute and per area) and (iv) the fisheries exploitation level, biological reference points and length-based indicators for sustainable levels of exploitation.

Although the stomach analysis was based on occurrence and numerical methods, two complementary approaches were used to analyse the length frequency data. The first was based on an analysis of the length frequency data using the TropFishR software (Mildenberger et al., 2017) in estimating growth parameters and exploitation rates from a catch-curve analysis. The second was based on the use of length-based indicators (Cope and Punt, 2009; Froese, 2004) in estimating the spawning potential of the species under the current exploitation regime.

5.2 Materials and methods

5.2.1 Description of the study sites

Lake Tono (10°52′48″ N, 1°9′36″ W) (Figure 5.1) is the largest artificial lake in the upper east region of Ghana, with a surface area of 18.6 km^2. Lake Bontanga (9°33′0″ N, 1°1′12″ W; Figure 5.1) is about one-third of this size (6.7 km^2), but it is the largest artificial lake in the northern region of Ghana. Lake Tono is approximately 210 km away from Lake Bontanga. Lake Tono has a length of 3 471 m and a catchment area of 650 km^2. Its mean depth is 6.6 m and its volume is estimated as 93 ×10^6 m^3. Lake Bontanga, conversely, has a length of 1 900 m and a catchment area of 165 km^2, a mean depth of 5.9 m and a water volume capacity of 25 × 10^6 m^3. Both systems are within the Guinea savanna belt where the most prominent rainy season is from June to October. The lakes were primarily constructed to support irrigation agriculture. The fisheries resources of both lakes have provided livelihood opportunities to fishers in the riparian communities for the past four decades. Lake Bontanga has two main landing sites (Voggu and Bontanga), whereas Lake Tono has five landing sites. The catch at Lake Bontanga is dominated by tilapias (73%), *Clarias gariepinus* (9%), *Brycinus nurse* (5.9%), *A. occidentalis* (3%), *Heterotis niloticus* (2.4%) and *Mormyrus* spp. (2.4%). Other landed species include *Malapterurus electricus, Labeo* spp*.*, *Hemichromis* spp., *Citharinus citharinus, Distichodus engycehpalus, Ctenopoma kingsleyae, Pellonula leonensis, Polypterus endlicheri* and *Protopterus annectens.* The total annual catch at Lake Bontanga (from July 2016 to June 2017) was 105.8 tonnes. Similarly, at Lake Tono, catches were dominated by tilapias (89%), *A. occidentalis* (4.1%), *Schilbe* spp. (3.2), *Clarias gariepinus* (1.1%) and *Hemichromis* spp. (1.1%). The rest include *Pellonula leonensis, Labeo* spp*.*, *Mormyrus* spp., *Synodontis* spp. and *Heterotis niloticus*. The total catch at Lake Tono (from July 2016 to June 2017) was 187.2 tonnes.

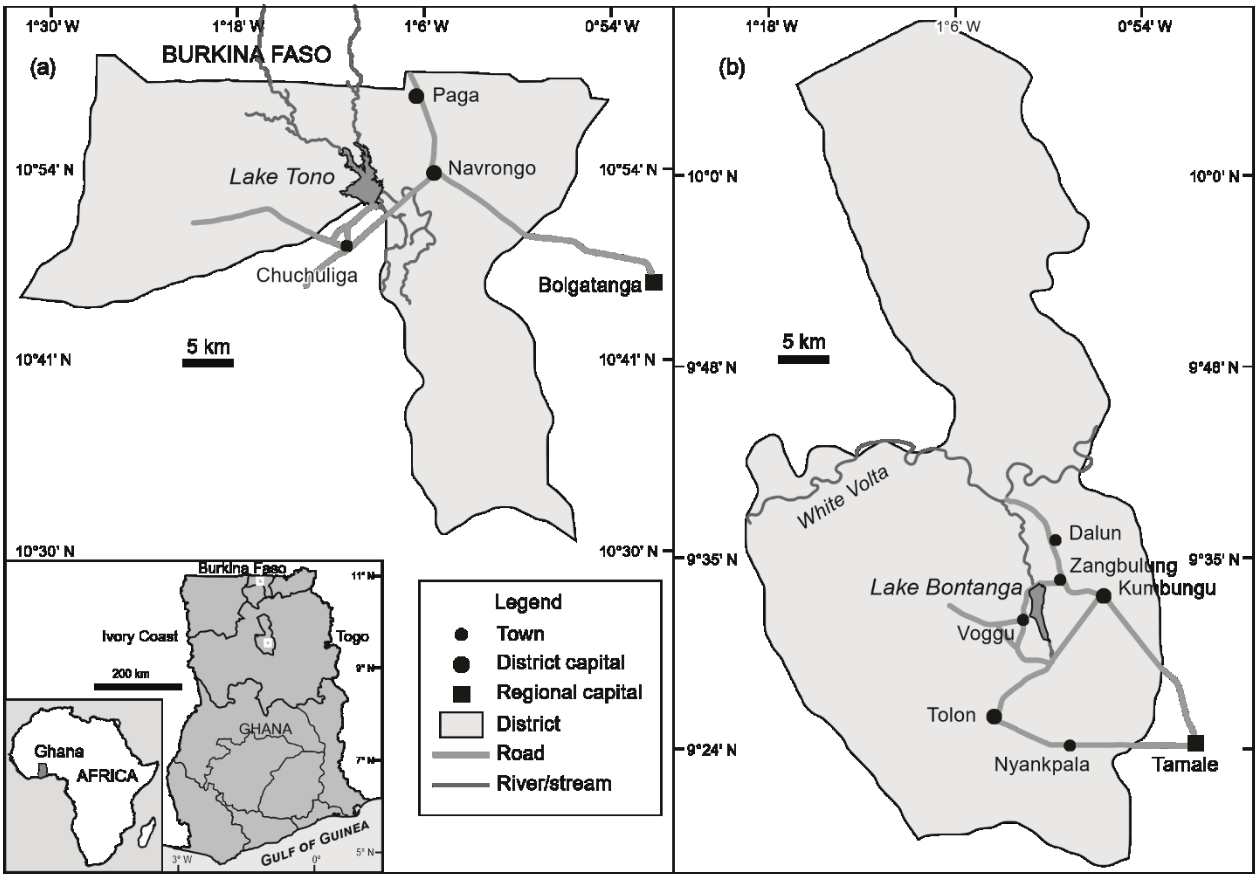

Figure 5.1. Map showing the locations of Lake Tono in Kassena Nankana East Municipal (formerly Kassena Nankana Municipal) and Lake Bontanga in Kumbungu District (formerly Tolon-Kumbungu district).

5.2.2 Fish sampling

Fish specimens were collected each month from fishers operating in Lake Bontanga and Lake Tono. The fish were caught by nylon monofilament gill nets with mesh sizes ranging from 22 to 57 mm at Lake Bontanga and from 51 to 70 mm at Lake Tono. The twine diameter ranged between 0.10 and 0.16 mm. The height of the nets ranged from 1 to 2.5 m. Hook and lines were used occasionally to target the species. Fish measurements of standard and total lengths were done using a fish measuring board to the nearest 0.1 cm and specimens were weighed with a weighing scale to the nearest 0.01 g. Fish samples were taken for a period of six months from July to December 2016 for stomach content analysis, whereas the size frequency data were collected for one full year (from July 2016 to June 2017).

5.2.3 Stomach content analysis

Individuals of *A. occidentalis* from both lakes were obtained fresh from the fishers and kept in an ice box to prevent post-mortem digestion. In the Spanish laboratory of the University for Development Studies, Nyankpala campus, Ghana, the fish were dissected, the guts removed and the contents were taken with a dropper, placed on slides and examined under a microscope. Stomach contents were analysed using the frequency of occurrence and “points” method (Hyslop, 1980). The frequency of occurrence method estimates the percentage of stomachs in a sample containing a given food item whereas the “points” method gives the bulk contribution of each food item to the total food consumed. The “points” method is considered one of the most convenient methods for assessing the feeding habits of herbivorous and omnivorous fish species because, they feed on microorganisms and it is more complex to measure volumes of food items containing microscopic organisms such as algae and diatoms when using other methods (Zacharia and Abdurahiman, 2004). Points were given to stomachs which were fully filled, half-filled and quarterly filled respectively. However, empty stomachs were completely excluded from the analysis. The total number of points given to each stomach was subdivided among the food items present according to their relative contribution to the total stomach content. The percentage composition of each food items was determined by summing up the points awarded to the item and dividing it by the total points awarded to all stomachs containing food and the resulting value was expressed as a percentage. It should be noted that points of 10, 5 and 2.5 represent 100%, 50% and 25% respective contribution of a food item to the stomach content of the fish.

Frequency of Occurrence of food item:

$$\frac{\text{Total number of stomach with a particular food item}}{\text{Total number of stomachs with food}} \times 100$$

Points of food item:

$$\frac{\text{Number of points of the particular food item}}{\text{Total number of points of all food items}} \times 100$$

The R programming software (Version 3.5.0) was used for the statistical analysis. Tests for normality were done using the Anderson–Darling normality test (Ad.test) and the Cramer–von Mises normality test (Cvm.test). The results of the normality tests on the food items indicated that the *p*-values on all food categories by both tests were below the conventional value of 0.1. Therefore, a comparison of the sample means (between Lake Bontanga and Lake

Tono) of the food items followed a non-parametric procedure using a Wilcoxon rank-sum test instead of a Student's *t*-test.

5.2.4 **Stock assessment approach**

TropFishR (Mildenberger et al., 2017), an R package for tropical fisheries analysis, was used for the stock assessment. TropFishR has enhanced functions of the FAO-ICLARM Stock Assessment Tools II FISAT II (Gayanilo et al., 2005). It includes some additional recent methods. The length frequency data (LFQ) were raised to the monthly catches observed for the species before conducting the electronic length frequency analysis (ELEFAN), catch-curve analysis, virtual population analysis (VPA) and yield per recruit analysis (YPR). The total weight of *A. occidentalis* landed at each lake was observed and recorded for five fishing days per month and using the average number of fishing days, the total catch was extrapolated. The LFQ data were raised to match up with monthly catches, with the assumption that the number and weight of fish measured for the LFQ data are an adequate representation of the length distribution of the total catch for the month. The individual steps of the length-based stock assessment, outlined by Sparre and Venema (1998) and for TropFishR by Mildenberger et al. (2017), were implemented within a bootstrapping framework (Schwamborn et al., 2019). This allows to estimate uncertainty intervals for all parameters and avoid the seed effect (Schwamborn et al., 2019).

5.2.5 **Growth parameters**

Total length measurements grouped into 1 cm class intervals were used to assess the growth parameters of the species, using a seasonally oscillating von Bertalanffy growth equation (soVBGF) (Pauly and Gaschutz, 1979; Somers, 1988):

$$L_t = L_\infty\left(1 - e^{-(K(t-t_0)+S(t)-S(t_0))}\right),$$

where L_t is the total length of the fish at time t, L_∞ is the asymptotic length of fish in cm, K the rate at which Lt approaches L_∞ and t_0 is the theoretical age of the fish when Lt is equal to zero. In $S(t) = (CK/2\pi) \sin 2\pi(t - t_s)$, C is a constant indicating the amplitude of the oscillation, typically ranging from 0 to 1 (a value >1 implies periods of shrinkage in length, which is rare) and t_s is the fraction of a year (relative to the age of recruitment, $t = 0$), where the sine wave oscillation begins (i.e. turns positive). A seasonally oscillating VBGF was used to assess the growth parameters, because seasonal changes in the growth of tropical fish have frequently been reported, which are attributed to changes in water temperature, precipitation and/or to the availability of food (Herrón et al., 2018; Morales-Nin and Panfili, 2005). The bootstrapped

ELEFAN with genetic algorithm optimisation (bootstrapped ELEFAN with genetic algorithm (GA)) function of TropFishR (Mildenberger et al., 2017; Schwamborn et al., 2019) was used to determine the parameters L_∞ and K of the von Bertalanffy equation. An initial seed value of L_∞ was based on $L_{\max}$, derived from the mean of the 1% largest fish in the sample and following the equation of Taylor (1958): $L_\infty = L_{\max}/0.95$. The VBGF parameters were assessed using a moving average (MA) over seven size intervals. Because the VBGF parameters are known to be sensitive to the MA setting (Taylor and Mildenberger, 2017), the bootstrapped ELEFAN with a GA function was also rerun for each assessment with MA over five and nine size intervals, respectively. The genetic algorithm (GA) is an optimisation approach for growth function fitting, using the open-source software 'R' (Taylor and Mildenberger, 2017).

The L_∞ and K were used to calculate the growth performance index (Ø') = $\log K + 2\log L_\infty$ (Pauly and Munro, 1984) to compare the growth performance of the giraffe catfish between the two lakes. The bootstrapping approach included in the TropFishR allowed for the estimation of confidence intervals around the mean growth parameter estimates. The parameter t_{anchor} indicates the fraction of the year where yearly repeating growth curves cross length equal to zero.

5.2.6 Mortality and exploitation rate

The instantaneous total mortality coefficient (Z) was estimated by means of the linearised length-converted catch-curve analysis method incorporated in the TropFishR package using the relation: $\mathrm{Ln}(\mathrm{N}i/\mathrm{d}ti)$ 'with age t or relative age', where Ni is the number of individuals in length class i and dti the time needed by the fish to grow in class i (Pauly, 1990; Pauly et al., 1995). The rate of natural mortality (M) was estimated according to the empirical equation of Then et al. (2015):

$$M = 4.118K^{0.73}L_\infty{}^{-0.33}$$

Fishing mortality rate (F) was estimated using the relationship: $F = Z - M$. The exploitation rate (E) was obtained from: $E = F / Z$. Estimated values of E were then compared with a reference value of 0.5, which has been proposed as an upper level of sustainable exploitation for fish species (Gulland, 1971). The estimated exploitation rates were derived from maximum density values of distributions for each parameter obtained from the linearised length converted catch curve, using a bootstrapping approach. Although F and M add up to Z on the level of the resamples, the maximum density estimates (and medians) do not have to add up, because the maximum density of each distribution is determined independently from the other parameters.

The total mortality (*Z*) was estimated using both the conventional linearised length-converted catch curve and the bootstrapping approach.

5.2.7 Size at first capture

The size (L_c) at which 50% of the fishes are retained by the gear, was estimated using the ogive selection of the bootstrapped linearised length-converted catch curve, assuming that the chance of capturing a fish is solely dependent on its length.

5.2.8 Stock size estimates

Cohort analysis (Jones, 1984) was conducted to study the dynamics of the fish stocks and to estimate fishing mortality for different length groups using the estimated L_∞ and *K* values. The annual mean value of *F* derived through the length converted catch curve was used as an estimate for the fishing mortality of the last length group (‘terminal *F*’). The last length groups, with low catch numbers, were grouped into one plus group. Biomass of the different length groups was then calculated with the length-weight relationship (LWR) equation, using the constant *a* and the exponent *b* values, derived from the study data (Table 5.1). The cohort analysis is based on the following equations:

$$N_{i+1} = N_i exp\big(-(F_i + M)\big)$$

$$C_i = N_i \frac{F_i\big(1-exp\big(-(F_i+M)\big)\big)}{F_i+M},$$

where *N* is the stock size in numbers, *C* is the catch, *F* is the fishing mortality and M is the natural mortality.

Table 5.1. Descriptive variables and length-weight relationships of *A. occidentalis* from lakes Bontanga and Tono.

Variable	Symbol	Bontanga	Tono
Total number of specimens	N	1553	798
Total length (cm)	TL range	6.3-36.5	12.4-50.2
Body weight (g)	BW range	4.3-479.6	17.6-1400.6
Length at first capture (cm)	Lc (Cl95%)	14.3 (12.4-15.7)	29.07 (24.4-30.7)
Mean catch length (cm)	*Lmean*	17.2	27.6
Time corresponding to L_c (yr)	t_{50}	2.3	3.8
Constant	a (Cl95%a)	0.012 (0.011-0.013)	0.0073 (0.006-0.009)
Allometric coefficient	b (Cl95%b)	2.93 (2.90-2.97)	3.10 (3.06-3.15)
Coefficient of determination	r^2	0.9544	0.9528

5.2.9 Relative yield per recruit Y'/R and reference points

The fishing mortality that produces the highest biomass per recruit ($F_{\max}$), the fishing mortality that will result in 50% reduction of the biomass of unexploited population ($F_{0.5}$) and a fishing mortality that corresponds to 10% of the slope of the yield-per-recruit curve at its origin ($F_{0.1}$) were predicted using the Thompson and Bell model (Thompson and Bell, 1934). The model builds on the output of the cohort analysis with the following input parameters: K (annual growth coefficient); t_{anchor} (anchor point); L_∞ (asymptotic length); M (natural mortality); a (constant of LWR); b (exponent of LWR); L_r (length at recruitment to fishery); L_{50} and L_{75} (selectivity parameters) (Sparre and Venema, 1998; Thompson and Bell, 1934). The reference points $F_{\max}$, $F_{0.5}$ and $F_{0.1}$, with their confidence intervals, were used as the first set of indicators of the exploitation status.

5.2.10 Length-based indicators for sustainable fisheries

Three indicators proposed by Froese (2004) formed the second set of indicators for the assessment of stock status. The indicators are:

- P_{mat}: refers to the proportion of mature fish in the catch, with 100% as the reference target point, based on the equation: P_{mat} = % fish in sample > L_m; where L_m is the length at first sexual maturity. This suggests that all fish should be allowed to spawn at least once before they are caught to rebuild and maintain healthy spawning stocks.The L_m values used were taken from studies by Kwarfo-Apegyah (2008) and Akongyuure et al. (2017b). The corresponding total lengths at first sexual maturity were 14.8 and 17.8 cm for Lake Bontanga and Lake Tono, respectively.

- P_{opt}: is the proportion of fish within a 10% range around the optimum length (L_{opt}) in the catch, with 100% as the reference target, based on the equation: P_{opt} = % fish > L_{opt} − 10% and < L_{opt} + 10%; where: $\log(L_{opt}) = 1.053*\log(L_m) - 0.0565$ (Froese and Binohlan, 2000). The L_{opt} for the target species based on the equation were 15.0 cm and 18.2 cm at Lake Bontanga and Lake Tono, respectively.
- P_{mega}: indicates the proportion of 'megaspawners' in the catch, with 30% to 40% as a desired target reference point, based on the equation: P_{mega} = % fish > L_{opt} + 10% (Froese, 2004).

Using a decision tree procedure by Cope and Punt (2009), the three proportions were summed ($P_{mat} + P_{opt} + P_{mega}$) to obtain P_{obj}, which defines indicator values of stock status above spawning stock biomass (SSB) reference points. The P_{obj} allows for differentiation of selectivity patterns, because the authors observed that P_{obj} had a more consistent relationship with spawning stock biomass (SSB) than any of the individual metric (P_{mat}, P_{opt} or P_{mega}) and that different selectivity patterns in the fishery were associated to a range of values of P_{obj}. Once a selectivity pattern is established, based on P_{obj}, threshold values of P_{mat}, P_{obj} and/or the L_{opt}/L_m ratio point to an estimated probability of the spawning stock biomass (SSB) being below established reference points, either 40% or 20% of the unfished spawning stock biomass (0.4SSB or 0.2SSB) is established.

5.3 Results

5.3.1 Food spectrum of *Auchenoglanis occidentalis*

Lake Tono had more full and half-full stomachs than Lake Bontanga, whereas quarter-filled stomachs were more predominant in Lake Bontanga. Of the 72 stomachs of *A. occidentalis* examined from Lake Bontanga, 35% were empty. Of the 47 stomachs with food, 34.04% were fully filled, 29.8% were half filled and 36.2% were quarter filled. Of the 82 stomachs of *A. occidentalis* examined from Lake Tono, 27% were empty. Of the 73% stomachs containing food, 44.1% were fully filled, 32.2% were half filled and 23.7 were quarter filled.

The food items identified were insect larvae, adult insects, digested food, fish parts, sand and silt particles, algae, other plant material and zooplankton. Insect larvae and fish parts occurred in 30% and 3.3%, respectively, of the total stomachs examined at Lake Bontanga and in 35.6% and 3%, respectively, of those examined at Lake Tono (Figure 5.2). Similarly, insect larvae and fish parts had the highest and the lowest bulk contributions, respectively, to the stomach contents of the fish from Lake Bontanga (43.8% and 1.8%) and Lake Tono (49.3% and 1.1%) (Table 5.2; Figure 5.3). No significant difference in the bulk contribution of food items was found between the stomach contents of *A. occidentalis* from Lake Bontanga and Lake Tono (Table 5.3).

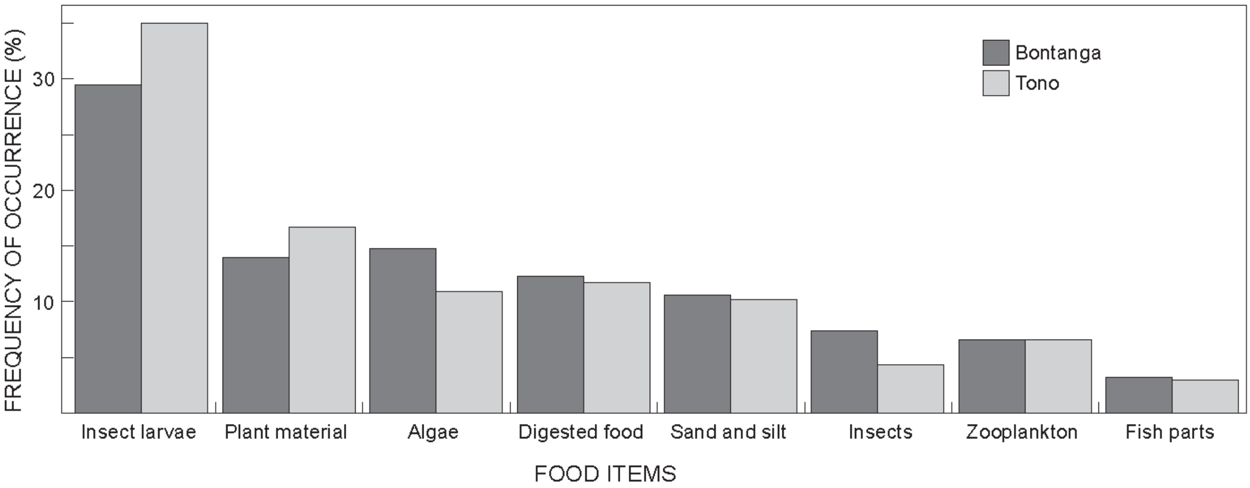

Figure 5.2. Frequency of occurrence of food items in the stomachs of *A. occidentalis* from lakes Bontanga and Tono.

Table 5.2. Total points and bulk contribution of food items to the stomach contents of *A. occidentalis* from lakes Bontanga and Tono.

	Bontanga		Tono	
	Total points	Contribution (%)	Total points	Contribution (%)
Algae	38.5	14.2	39.5	10.6
Digested food	50	18.5	65.0	17.5
Fish parts	5	1.8	4.0	1.1
Insect larvae	118.5	43.8	183.5	49.3
Insect parts	9	3.3	9.0	2.4
Plant material	23.5	8.7	35.0	9.4
Sand and silt particles	19.5	7.2	24.0	6.5
Zooplankton	6.5	2.4	12.0	3.2
Total	270.5	100.0	372	100

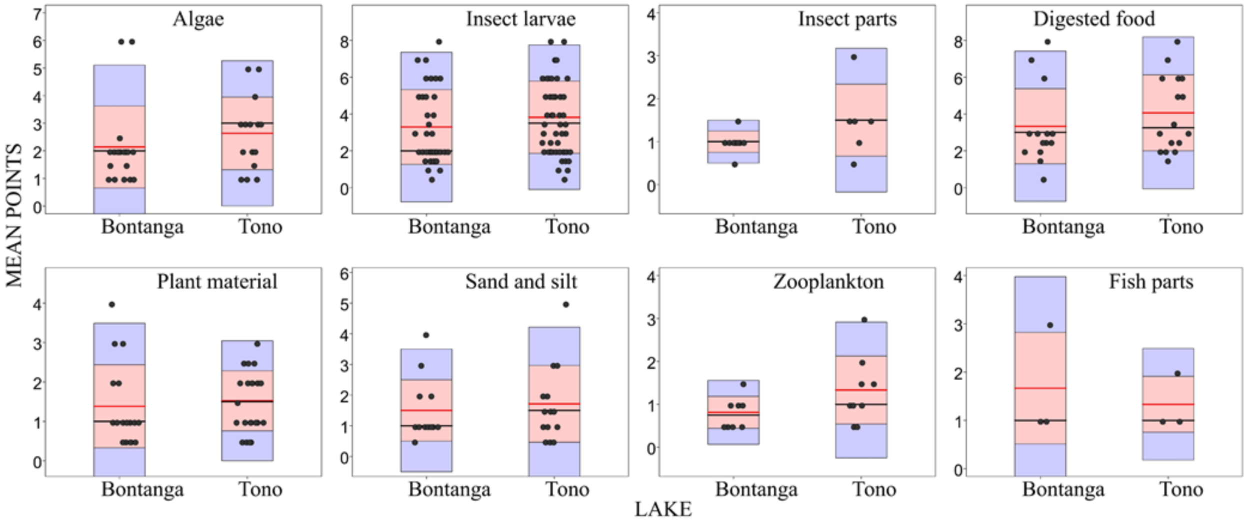

Figure 5.3. Mean point distribution of food items found in the stomach *Auchenoglanis occidentalis* from Lake Bontanga and Lake Tono. Points 10, 5 and 2.5 represent stomachs that are fully filled, half-filled and quarterly filled, respectively. The lower quartile, median (black line), mean (red line) and upper quartile are indicated.

Table 5.3. Wilcoxon rank sum test with continuity correction and mean points of food items from Bontanga and Tono man-made lake systems. It should be that due to limited data, fish parts are not included in the comparison. α at 5% significance level.

Food items	Mean points ± SD of food items from Bontanga	Mean points ± SD of food items from Tono	Wilcoxon rank sum test	P-value (0.05)
Algae	2.14 ± 1.48	2.63 ± 1.32	95.5	0.147
Digested food	3.33 ± 2.04	4.06 ± 2.06	100	0.435
Insect larvae	3.29 ± 2.03	3.82 ± 1.96	704.5	0.147
Insects	1 ± 0.25	1.5 ± 0.84	14.5	0.121
Plant materials	1.38 ± 1.05	1.52 ± 0.76	161.5	0.343
Sand and silt	1.5 ± 1	1.71 ± 1.25	82.5	0.686
Zooplankton	0.81 ± 0.37	1.33 ± 0.79	20.5	0.13

5.3.2 Size composition

The *A. occidentalis* populations at Lake Tono and Lake Bontanga had total length ranges of 12.4 to 50.2 cm and 6.3 to 36.5 cm, respectively (Annex III, Figure S5.1). This size range difference is evident by the estimates of length at first capture (L_c) and mean catch length (L_{mean}). Both estimates were significantly higher for Lake Tono than for Lake Bontanga. The time corresponding to the L_c indicates that the mean age of the catch at Lake Bontanga is 2.3 years and 3.8 years at Lake Tono (Table 5.1; Annex III, Figure S5.4).

5.3.3 Growth parameters

The asymptotic length (L_∞) for the fish populations at Lake Bontanga is approximately 10 cm lower than the estimate for the populations at Lake Tono. Although K was close in range for both systems (Table 5.4; Figure 5.4), the growth performance index is substantially higher at Lake Tono. The estimates of the parameter t_{anchor} indicate that August and September are the months close to the hatching period, where the yearly repeating growth curves cross the length equal to zero for the populations at Lake Tono and Lake Bontanga, respectively. The confidence intervals around the growth parameters were similar for both systems (Table 5.4; Annex III, Figures S5.2 and S5.3).

Table 5.4. Parameter estimates of seasonalised von Bertalanffy growth function for *A. occidentalis* specimens from lakes Bontanga and Tono assessed with the bootstrapped electronic length frequency analysis with genetic algorithm function of TropFishR. Estimates based on length-frequency samples collected from July 2016 to June 2017. Max., maximum density and Lower and Upper denote 95% confidence interval of the estimates.

Parameter	Symbol	Bontanga			Tono		
		Max.	Lower	Upper	Max	Lower	Upper
Asymptotic length	L_∞ (cm)	28.91	27.19	35.62	38.27	36.25	42.25
Coefficient of growth rate	K (yr)	0.31	0.12	0.43	0.34	0.19	0.48
	t_{anchor}	0.72	0.12	0.87	0.60	0.20	0.77
	C	0.68	0.16	0.93	0.49	0.25	0.83
	Ts	0.45	0.14	0.78	0.73	0.24	0.82
Growth performance index	Φ	2.41	1.93	2.74	2.70	2.40	2.93

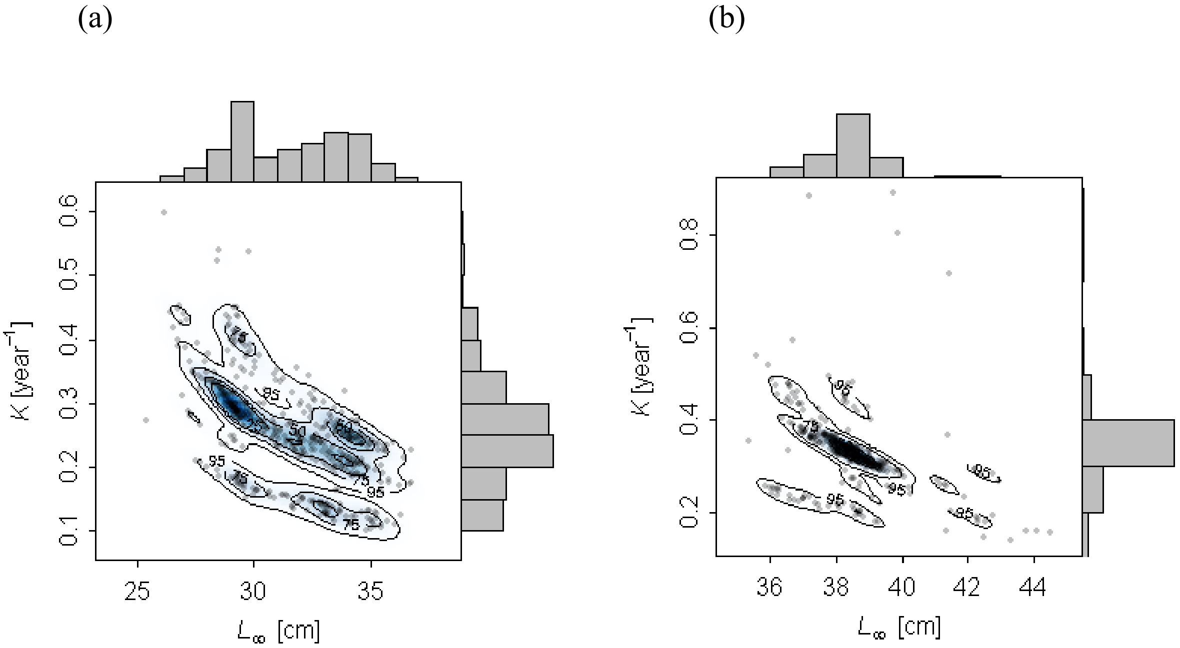

Figure 5.4. Scatter histogram of bootstrapped ELFFAN with genetic algorithm optimisation for *A. occidentalis* collected from (a) Lake Bontanga and (b) Lake Tono. Dots represent estimated L∞ and K (growth parameters of the von Bertalanffy function) per resampled length-frequency catch data.

5.3.4 Mortality and exploitation rate

The populations at Lake Tono had higher natural mortality than fishing mortality, whereas the reverse is true for the populations at Lake Bontanga. Consequently, the exploitation rate is was significantly higher at Lake Bontanga than Lake Tono. The maximum density values suggest that the fish populations are underexploited in Lake Tono, whereas the upper limit of the confidence interval of the exploitation rate for the populations at Lake Bontanga is above the recommended optimal exploitation level (E = 0.5) (Table 5.5). The exploitation rates of the fish stock remained unchanged for the populations at Lake Tono, when the assessment was rerun with MA setting of five and nine. However, the exploitation rates for the populations at Lake Bontanga, when assessed with MA settings of five and nine size intervals were slightly above the optimal exploitation rate (Annex III, Table S5.1 and S5.2). The total mortality values estimated using the conventional length-converted catch curves (Figure 5.5) were consistent with those obtained with the bootstrapped, linearised length-converted catch curves, but with different confidence intervals (Table 5.5; Annex III, Figure S5.3). Because the bootstrap approach allowed for unbiased selection of data points in the length-converted catch curve for the estimation of total mortality (Z), the results of that approach (Table 5.5) were used for the yield-per-recruit analysis and stock size estimation.

Table 5.5. Mortalities (Z, M and F), exploitation rate (E) biological reference points of fishing mortality (Fmax, F0.1, F0.5) and stock size estimates of *A. occidentalis* from lakes Bontanga and Tono. Lower and upper denote 95% confidence interval of the estimate. Estimates are based on the bootstrapping approach.

Parameter	Bontanga			Tono		
	Max.	Lower	Upper	Max	Lower	Upper
Z	1.04	0.38	1.62	0.73	0.44	1.04
M	0.47	0.27	0.74	0.55	0.36	0.73
F	0.50	0.09	0.90	0.17	0.01	0.42
E	0.48	0.24	0.56	0.23	0.02	0.40
F0.1	1.04	0.68	2.05	1.00	0.66	1.84
Fmax	1.86	1.24	4.37	4.14	2.25	7.00
F05	0.59	0.39	1.39	0.89	0.54	1.72
N	369127	227215	2994478	550517	359142	16709314
B (tonnes)	12.17	7.09	124.18	57.97	43.68	1880.4

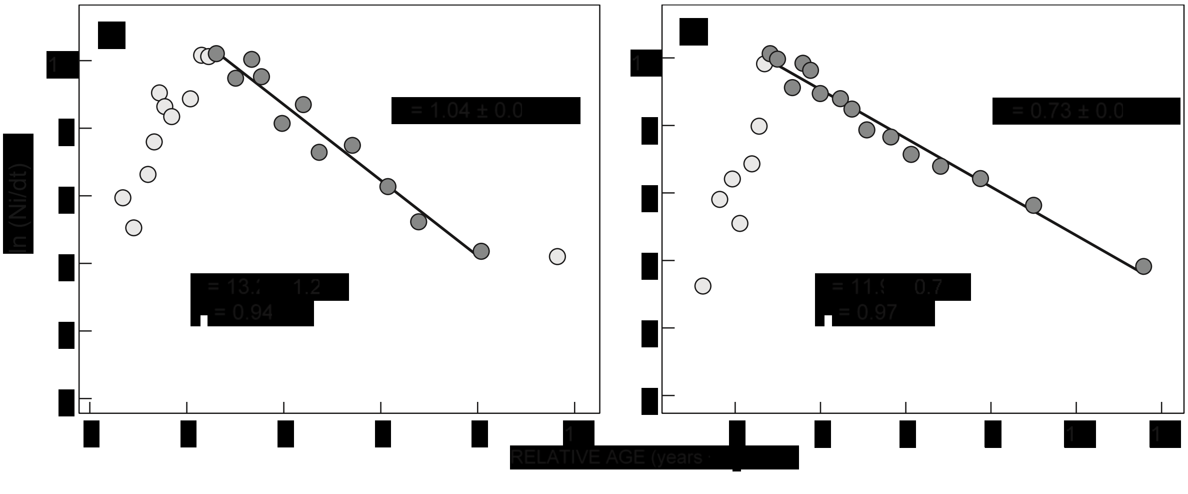

Figure 5.5. Linearised length-converted catch curves for *A. occidentalis* collected from (a) Lake Bontanga and (b) Lake Tono.

5.3.5 Stock biomass

The biomass of *A. occidentalis* per unit of lake area is substantially higher at Lake Tono (3.12 tonnes km^{-2}) than Lake Bontanga (1.82 tonnes km^{-2}) (Table 5.6).

5.3.6 Biological reference points

The $F_{0.1}$ values are similar for both systems, whereas F_{max} for Lake Tono is more than twice as high as the value for Lake Bontanga. Similarly, the $F_{0.5}$ of Lake Tono is higher than Lake Bontanga (Table 5.5).

5.3.7 Length-based indicators (LBI)

The proportion of immature fish in the catches was higher in Lake Bontanga than Lake Tono. Although the fish exploitation at Lake Tono met the 100% target reference for P_{mat}, the proportion of fish within the P_{opt} range was very low (0.4%) (Table 5.6). Additionally, the catches at Lake Tono were full of large-sized *A. occidentalis*, with the P_{mega} being above the desired target range of 30% to 40%. Lake Bontanga had a higher proportion of fish within the P_{opt} than Lake Tono. Moreover, the P_{mega} value for Lake Bontanga was within the desired target range. The decision tree analysis indicated that the spawning stock biomass of the stock at Lake Bontanga was below the reference point of 40% of the unfished biomass, whereas the stock at Lake Tono had a spawning stock biomass above this reference point (Table 5.6; Figure 5.6).

Table 5.6. Proportions of mature fish (Pmat), optimum-sized fish (Popt), larger than optimum size fish (Pmega) and Pobj (= Pmat + Popt + Pmega) for *A. occidentalis* from lakes Bontanga and Tono based on the indicators proposed by Froese (2004) and the formulas described in Methods. Stock condition interpretation is based on a decision tree proposed by Cope and Punt (2009), aimed to assess whether spawning biomass (SB) is above (>) or below (<) a reference point (RP) of 0.4 unfished biomass. The last column indicates the estimated probability of SB being lower than 0.4 of unfished biomass based on the same authors.

Variable	Bontanga	Tono
Pmat	0.77	1.00
Popt	0.26	0.004
Pmega	0.68	0.99
Pobj	1.70	1.99
Stock condition interpretation	SB < RP	SB > RP
Probability	100%	0%

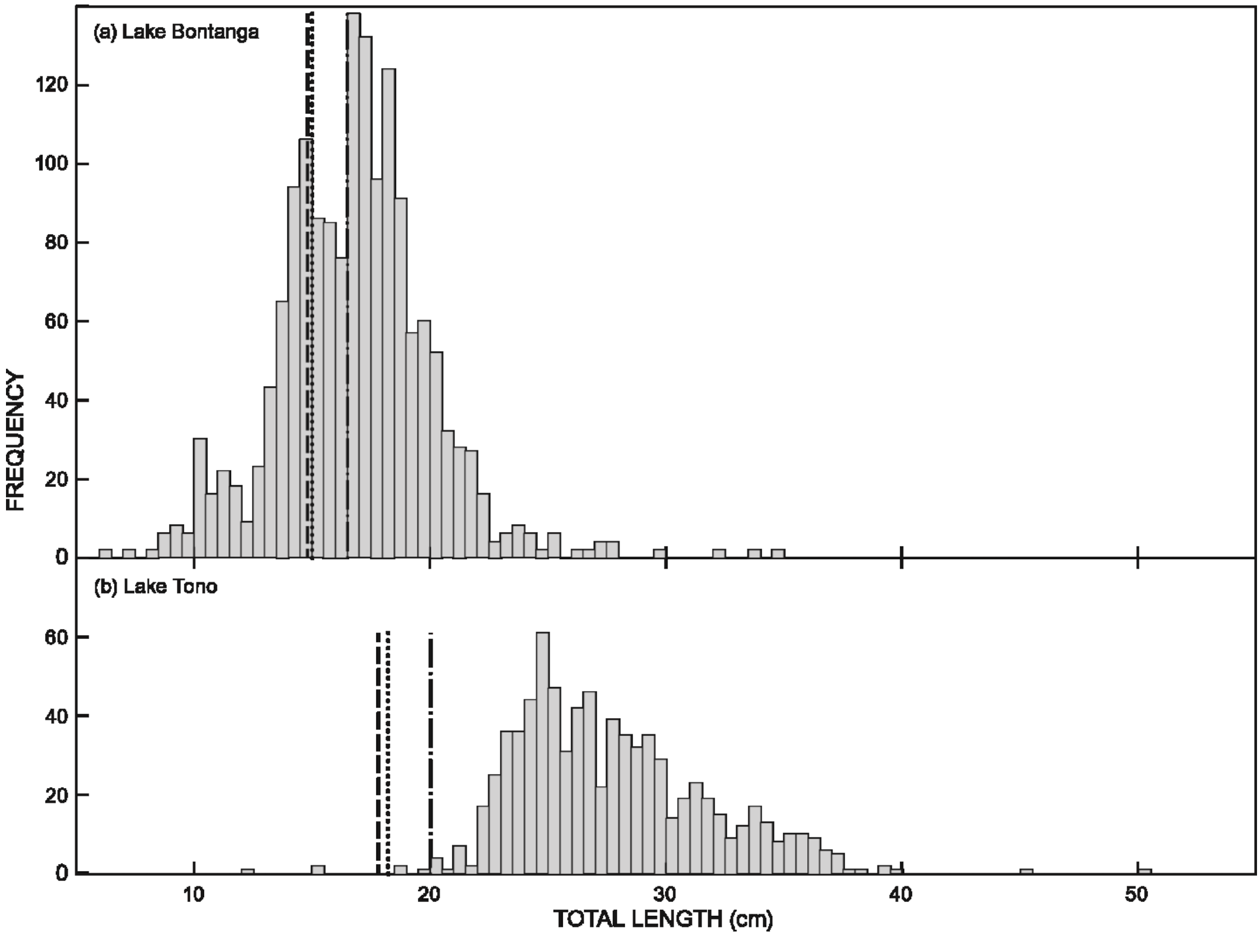

Figure 5.6. Size distribution of *A. occidentalis* landings observed from July 2016 to June 2017 at Lakes Bontanga and Tono. The vertical lines represent the length based reference values: length at first maturity (dashed line), optimum length L_{opt} (dotted line) and starting length of mega-spawners ('dot-dashed' line).

5.4 Discussion

5.4.1 Feeding habits of *Auchenoglanis occidentalis*

The food items recorded in this study for the giraffe catfish *Auchenoglanis occidentalis* are similar to those found by Ikongbeh et al. (2014), who reported that *A. occidentalis* from Lake Akata, Nigeria, fed on a variety of food items ranging from insect larvae to algae and considered *A. occidentalis* to be omnivorous. *Auchenoglanis occidentalis* from Lake Bontanga and Lake Tono systems fed more on insect larvae than on algae. The high percentage of insect larvae encountered in the stomachs of *A. occidentalis* from Lake Tono and Lake Bontanga supports the findings of Eccles (1992), according to whom *A. occidentalis* occurs in shallow waters with a muddy bottom, where insects occur in the benthic zone of the aquatic environment and consequently their larvae are prone to be preyed on by *A. occidentalis*. Our findings also confirmed a study by Chukwuemeka et al. (2015), which indicated that the stomach contents of *A. occidentalis* population in Lake Tagwai, Minna Niger State, Nigeria, were dominated by insects (31.75%), fish (12.70%), chyme (20.63%), plant material (20.63%), protozoa (1.59%) and soil (12.70%). The dominance of insect larvae among the food items in both systems as observed from July to December could be related to the high rainfall that occurs during the flood and post-flood seasons of northern Ghana, during which insects find conditions suitable for reproduction in the lakes. The ecological niche for the giraffe catfish is very similar in both lakes, as evidenced by the similar food spectrum found through the stomach analysis. The generally higher stomach fullness and lower proportion of empty stomachs found for Lake Tono might be indicative of better food conditions in this lake.

Although Ouéda et al. (2008) reported seasonal shift in the diets of the fish population in a Sahelo-Soudanian artificial lake (Loumbila, Burkina Faso), a recent study by Chukwuemeka et al. (2015) noted that there was no remarkable difference in food composition of the species population in Lake Tagwai, Minna Niger State, Nigeria, between the dry and rainy season months. Additional studies on the species' feeding ecology are required, especially in the semi-arid lakes of sub-Saharan Africa, in order to gain a better understanding of the seasonal profile of the feeding behaviour of *A. occidentalis*.

5.4.2 Growth parameter estimates

Although K was similar in both lakes, L_∞ greatly differed between the lakes, with a higher value in Lake Tono (Table 5.4) resulting in a substantially higher growth performance estimate for this lake. This might reflect real differences in attainable sizes between lakes in relation to lake size and stock density, but could also have been the result of the higher fishing pressure in Lake Bontanga, causing a greater depletion of larger fish close to the size of L_∞. Overall, the estimated growth performance indexes for the giraffe catfish in Lake Bontanga and Lake Tono are lower than the one (Ø' = 2.92) reported for Lake Bangweulu, Zambia (Cosmas, 1992). Moreover, the estimate of the asymptotic length (L_∞ = 52.8) in Lake Bangweulu is far higher, possibly as a result of differences in fisheries impact and environmental conditions among Lake Bangweulu and Lake Bontanga and Lake Tono.

5.4.3 Fisheries exploitation and biological reference points

The exploitation of *A. occidentalis* in Lake Tono appeared to be low and it seems that fishing pressure could be increased to achieve higher yields. At Lake Bontanga, to the contrary, the stock already seemed fully exploited, if not slightly overexploited, and an additional increase in the species' exploitation rate is not advisable.

The estimates using the YPR model indicated that the fishing mortality rates of the stocks in both systems were below the rates ($F_{\max}$ values) predicted to maximise equilibrium yield per recruit for the stocks under the model assumption that continues recruitment would prevail, and were again lower than the rates which would maintain 50% of the stock biomass, denoting that the stocks are not overexploited in Lake Tono. However, considering our estimates of the current exploitation rates in both systems, the stock at Lake Bontanga does not appear to be underexploited (see also below the confirming LBI analysis). The stocks in this lake should be monitored every two years, where possible, to assess changes in exploitation and to improve management advice.

5.4.4 **Length based indicators**

Although the stock at Lake Tono has a spawning stock biomass above the reference point, indicating a state of uncritical and sustainable fisheries, more yield could be obtained if exploitation within the L_{opt} range is increased to 20% or 30%, although simultaneously reducing the fishing pressure on the large individuals. For Lake Bontanga, to the contrary, the pressure on immature individuals would have to be reduced in order to attain a sustainable fishery. Froese (2004) proposed reducing percentage of mature fish in the catch by 100% as a target and as a simple indicator, with the potential to allow more stakeholders to participate in fisheries management. The target indicator suggests that all (100%) fish should be allowed to spawn at least once before they are caught, in order to rebuild and maintain healthy spawning stocks. The proportion of 23% of immature fish in the catches at Lake Bontanga, and the low percentage of spawners in the population, might accordingly imply a current situation of both growth and recruitment overfishing.

5.4.5 **Stock biomass**

The estimates of the stock size show that per unit area, Lake Tono had nearly double the species population biomass than Lake Bontanga. This supports our findings with regard to the low current exploitation level, and the recommendation that the current exploitation rate of the species at Lake Tono could be increased to increase the yield. The estimate of the biomass of *Auchenoglanis* in Bagré reservoir in Burkina Faso is 1.64 tonnes km^{-2} (Villanueva et al., 2006), comparable with that of the stock size in Lake Bontanga. The low fishing pressure and higher biomass of the species in Lake Tono might be attributed to lower market availability around the Lake Tono area for the species' exploitation. The Navrongo market, which is the closest to Lake Tono, has not yet had much demand for smoked fish (the principal form of commercialisation), compared with the Tamale market, which is supplied by Lake Bontanga.

The larger biomass of Lake Tono accordingly seems to be a reflection of good growth conditions, stemming from a rich food supply and low fishing pressure allowing the population to flourish.

5.4.6 **Conclusion**

The giraffe catfish, *Auchenoglanis occidentalis*, populations in both systems exhibited omnivorous feeding behaviour, feeding more on insect larvae and as bottom feeders. Substantial amount of sand and silt particles were found in their stomach contents. The study did not reveal any significant difference in the bulk contribution of the food items from the Lake Bontanga and the Lake Tono artificial systems, but found a generally higher stomach fullness in Lake Tono.

The population size and stock density of *A. occidentalis* was larger in Lake Tono and the growth performance was better. Here the species attains substantially larger sizes and the estimated growth performance index exceeded that of Lake Bontanga (2.70 compared with 2.41 for Lake Bontanga). The exploitation rate of the species in Lake Tono is low. Complementarily, the LBI analysis and the estimates of the stock size indicate that the fishing mortality could be greatly enhanced (about doubled) to increase yield at Lake Tono, whereas at Lake Bontanga, fishing effort should not be increased, because the current exploitation rate is at an optimum, and the fishing pressure on immature individuals should be reduced, in order to prevent growth overfishing. We recommend that a full year's study on stomach contents should be carried out to assess seasonal variation in the range of food items available to *A. occidentalis* populations in Lake Tono and Lake Bontanga and suggest that the stock of both lakes should be monitored continuously.

CHAPTER 6: Comparative analysis of biodiversity, food web structure and fisheries productivity

Comparative assessment of biodiversity, food web structure and fisheries productivity of three man-made lakes in Ghana

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Abstract

Man-made lakes are important ecosystems that contribute to food security and livelihoods in many countries. Understanding food web dynamics and ecosystem functioning of these systems is crucial for developing sustainable ecosystem-based management strategies. With the aim to assess differences in production characteristics and food web structures, this study addresses three important Ghanaian man-made lakes (Tono, Bontanga and Golinga) through a food web modelling approach (Ecopath with Ecosim). The lakes differ greatly in morphology, generating lake specific conditions for fish growth and production. The mean trophic level of the catch was lowest in the largest and deepest reservoir (Tono), likely resulting from higher trophic level species occupying less accessible deep ‘refuge’ habitats. In the medium-sized and small shallow lakes, in contrast, a larger catch portion resembles high trophic level species. Lake Bontanga differs from the other reservoirs by having a lower human population impact, a significantly lower P/R ratio, a higher TB/TST ratio, a higher FCI, a higher D:H ratio as well as the greatest gross efficiency of the catch, all indicative for a more developed ecosystem. While the smallest lake had the highest fish production under optimal conditions of water supply, it is most vulnerable when being used for both irrigated agriculture and fisheries production, especially if climate change predictions of increasing frequencies of drought periods in the region hold true. Our work suggests that the use of man-made lakes and respective catchment areas should be assessed and managed carefully to prevent the loss of local nutrition and livelihoods contributions. By this, our work provides basis for the development of sustainable ecosystem-based management measures not only for these local ecosystems, but for other reservoirs exposed to human activities around the world.

Keywords: Ecopath with Ecosim; fisheries production; food web; Ghana, irrigated agriculture; lakes.

6.1 Introduction

Lake ecosystems, both natural and artificial, are important for people´s livelihoods and food sustenance throughout the global South. With increasing anthropogenic and climate change pressures on these ecosystems, effective and sustainable management of their fisheries is therefore essential. Advancing knowledge on the differences and or similarities in trophic relationships and resource productivities among man-made lakes can help scientists to better manage and plan for the construction of future artificial systems.

Lake ecosystem functioning and structural organisation are controlled by both internal and external factors such as natural predation, nutrient fluxes, abundance and composition of introduced species and fishing. Understanding the dynamics and the impacts of these factors on (top-down and bottom-up) structuring processes is therefore crucial for successful ecosystem-based fisheries management (Jeppesen et al., 1997; Kao et al., 2016).

Conventionally, depth, water chemistry and conductivity have been used to classify lakes and reservoirs (Rai and Hill, 1980; Talling and Talling, 1965) since these parameters appear closely related with productivity (Downing et al., 1990; Henderson and Welcomme, 1974; Ryder et al., 1974). Rawson (1938) was the first to suggest that factors affecting lake productivity could be grouped into climatic, morphometric, and edaphic. It has been shown that biological production in lake systems is partly controlled by lake morphology, nutrients and other environmental factors (Kolding and van Zwieten, 2012). Some of these studies suggest that fish productivity per unit area is negatively related with habitat volume, area, and mean depth since many aquatic processes are less intense, and fish is less abundant (per unit area) in larger water bodies attributed to decreased rates of nutrient recycling into the euphotic layer with these lakes (Downing, 2010). However, the question on how differences in lake morphology and physico-chemical characteristics shape artificial ecosystems productivity, development, maturity and resilience has as yet received only limited scientific attention.

Reservoirs are defined as man-made lakes and may either be embedded in a river network or not (Hayes et al., 2017). Hereafter, the use of the term reservoir refers to man-made lakes. Reservoirs have been characterized as being rather underdeveloped and unstable ecosystems due to (1) changes in the general status from riverine to lacustrine conditions, (2) eutrophication due to the nutrient input from surrounding rural communities and decomposition of important quantities of submerged plant material, (3) early stage of the succession of the (artificial) fish community and (4) the development of unregulated fishing activities (Villanueva et al., 2006). Multiple use of reservoirs for irrigational agriculture, animal watering and fisheries also influence food web dynamics and ecosystem maturity.

To evaluate ecosystem effects of fishing, to model the consequences of environmental changes for food web dynamics or to explore different management strategies and respective repercussions on ecosystem dynamics, the Ecopath with Ecosim (EwE) trophic modelling approach was developed (Christensen and Pauly, 1992; Christensen et al., 2000; Polovina and Ow, 1985). The software has already been used to assess fisheries and inform management of African and Asian reservoirs: Reservoir Bagré (Villanueva et al., 2006), Lake Ayamé (Traore et al., 2008) and Lake Koka (Tesfaye and Wolff, 2018) in Africa as well as Parakrama Samudra, Sri Lanka (Moreau et al., 2000) and Ubolratana reservoir, Thailand (Villanueva et al., 2008), and Wyra reservoir, India (Panikkar and Khan, 2008). General characteristics of tropical reservoirs often differ remarkably, due to their highly dynamic nature, with water levels and biological productivity largely depending on the inflowing water. Using the EwE software, these differences between lakes can comparatively be assessed and the level of development and organisation across such artificial ecosystems can be described as resulting from varying physical and environmental characteristics as well as from potential differences in harvest levels.

The trophic modelling approach of EwE can also be used to study trophic cascades (i.e. indirect effects of predators on plants via predation on herbivores) in lakes and reservoirs. The trophic cascade theory postulates that the disturbance of a trophic level has consequences ("cascading effects") over the connected trophic levels above and below (Ribeiro Filho et al., 2014). Lakes with seasonal changes from clear to turbid water conditions have been reported to often go through a "Fish–zooplankton–phytoplankton" cascade, starting with fish mortalities (due to low oxygen conditions), which then leads to shifts in zooplankton size structure and corresponding strong top-down effects on phytoplankton (Jeppesen et al., 1998; Pace et al., 1999).

Nilssen (1984) suggested that all major morphometric features and physical processes are important when tropical man-made lakes to be compared. Yet, models of tropical lakes, which are more dynamic and perhaps also more complex compared to temperate ones, rarely have physical processes incorporated in their construction and analysis.

This study focuses on three man-made lakes in northern Ghana (Tono, Bontanga and Golinga; Fig. 6.1) that vary in shape, surface area, mean depth, water level fluctuation, total water volume and intensity of resource use. This is, to our knowledge, the first attempt to assess and model the food web structure and dynamics of Ghanaian reservoirs, which represent important fishing grounds, in particular of commercially important cichlid species. The study comparatively analyses food web structures and fisheries characteristics of the three systems to provide input to ecosystem-based and sustainable management of the fisheries resources.

The specific objectives of this study were:

(i) To identify biological groups, their biomass, and their feeding interactions in order to construct food web models for Tono, Bontanga and Golinga reservoirs.

(ii) To assess differences in the flow structure between the three reservoirs modelled in terms of functional groups characteristics (relative biomass, species composition), primary production, transfer efficiencies between trophic levels, diet matrix and fish catch.

(iii) To identify those groups that are key ecosystem controllers in the flow networks of the different reservoir ecosystems and evaluate how differences in the physical features of the reservoirs relate to differences in food web structure and resource productivities.

We hypothesize that the lakes' differences in physical features (shape, mean depth, overall size, and water holding capacity, water throughflow) relate to differences in food web structure and resource productivities, with the smallest and shallow Lake Golinga being the most productive on a per unit area basis.

6.2 Materials and methods

6.2.1 Description of Tono, Bontanga and Golinga reservoirs

The study was conducted at 3 reservoirs: Tono (10° 52' 48" N; 1° 9' 36" W), Bontanga (9° 33' 0" N; 1° 1' 12" W) and Golinga (9° 21' 36" N; 0° 57' 14.4" W) (Fig. 6.1). Tono is the largest reservoir in the Upper East region of Ghana and has a surface area of 18.6 km^2, while Bontanga and Golinga are the largest two reservoirs in the Northern region of Ghana. Bontanga has an intermediate size of 6.7 km^2, while Golinga is a very small reservoir with a surface area of only 0.62 km^2. The reservoirs are within the Guinea Savanna belt where the most prominent rainy season lasts from June to October. Tono, Bontanga and Golinga were constructed in 1985, 1983 and 1974, respectively (Gordon, 2006), primarily to support agriculture irrigation.

However, over time, they have become important inland fishing grounds (see Table 6.1 for further description).

Besides the lakes' morphological differences, the number of households (an indicator of pressure on the resources) that depend on the reservoirs for their livelihoods also vary in relation to the reservoir size with 16250, 4950 and 900 people in the communities around Tono, Bontanga and Golinga, respectively (Namara et al., 2011; Ghana Statistical Service, 2012; SGP, 2012).

Table 6.1. Seasonal fluctuation in surface area and water level of Tono, Bontanga and Golinga reservoirs from July 2016 to June 2017. The wet season, August 2016; dry season, April 2017. For an overview of seasonal variation of water level, turbidity and Secchi depth see Annex IV, Fig. S6.1.

Parameter	Tono	Bontanga	Golinga
Surface area during wet season (km^2)	18.6	6.7	0.62
Surface area during dry season (km^2)	12.5	3.8	0.3
Seasonal reduction in surface area (%)	32.8	43.3	51.6
Catchment area (km^2)	650	165	124
Mean depth (m)	6.6	5.9	2.7
Maximum depth (m)	13.32	9.70	4.95
Mean Secchi depth transparency (m)	0.73	0.49	0.38
Length of reservoir (m)	3471	1900	690
Water level: wet-dry (m)	10.5-5.04	8.23-2.85	2.8-0.12
Water level variation (m)	5.46	5.38	2.68
Water holding capacity (m^3)	93×10^6	25×10^6	1.23×10^6
Surface area: water volume ratio	0.20	0.27	0.50
*Relative Reservoir Level Fluctuation	82.7	91.2	99.6

Adapted from (Jul-Larsen et al., 2003): (mean reservoir level amplitude/mean depth) 100

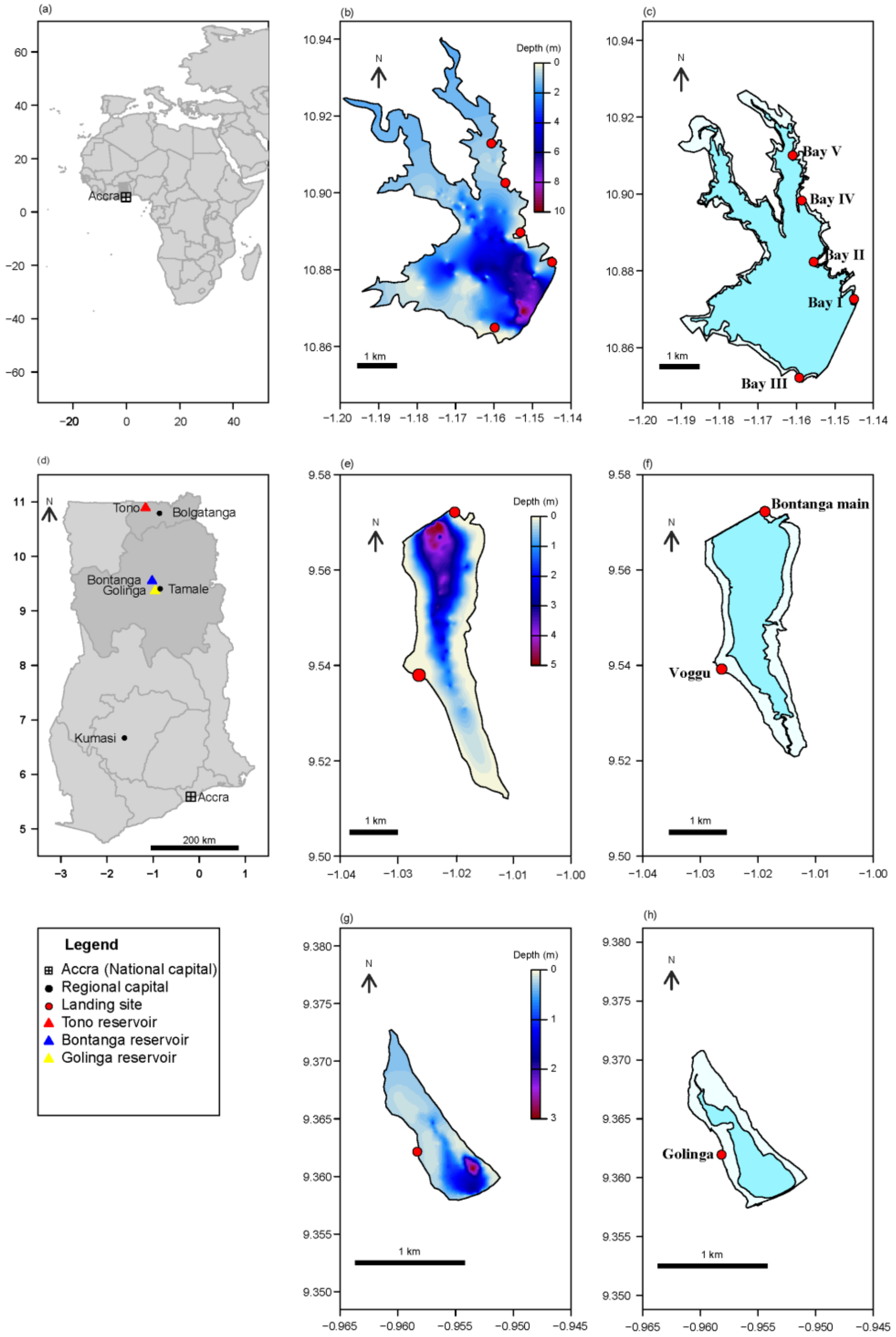

Figure 6.1. Overview maps of the African continent (a) and Ghana (d), indicating the location of national and regional capital cities, as well as the three reservoirs studied in this work. Bathymetric maps of Tono (b), Bontanga (e) and Golinga (g) reservoirs in Ghana, showing landing sites. The bathymetric data were obtained during the dry season (March-April 2017). Reservoir maps depicting the surface areas of the reservoirs during dry season (in blue; estimated on 03/04/2017, 25/04/2017 and 26/04/2017, in Tono (c), Bontanga (f) and Golinga (h), respectively) and wet season (in grey; estimated on 24/08/2016 and 14/08/2016 in Bontanga and Golinga, respectively). The area of the Tono reservoir during wet season was adapted from Google Earth. For exact values consider Table 6.1.

6.2.2 The Ecopath modelling approach

Ecopath with Ecosim (Christensen and Pauly, 1992; Christensen et al., 2000; Polovina and Ow, 1985) was used to construct trophic models of the Tono, Bontanga and Golinga ecosystems. To do so, the various organisms inhabiting each ecosystem were grouped into functional compartments considering as grouping criteria, their common physical habitat, similarity in food preferences and life history characteristics (Yodzis and Winemiller, 1999). The model input parameters (for each compartment) are annual mean biomasses, rates of production per biomass (P/B) and consumption per biomass (Q/B). All model compartments are linked through a diet matrix of prey-predator's connections. Fishery catches are considered "export" of the system.

Usually, an equilibrium condition is assumed for the model period considered, where group inputs are balanced to their outputs. Input data are standardized and units (wet weights) are expressed as t km^{-2}. Ecopath expresses each term in a budget equation as a linear function of the mean biomass of each group (i), which results in a system of simultaneous equations for each model group expressed as:

$$B_i * \left(\frac{P}{B}\right)_i * EE_i = \sum \left(B_j * \left(\frac{Q}{B}\right)_j * DC_{ji}\right) + EX_i + E_i + BA_i \qquad (1)$$

where B_i is the biomass of the group i; P/B_i is its production rate; B_j the biomass of any predator j of the prey i; Q/B_j the food consumption rate of j; DC_{ji} is the fraction of i in the diet of j, expressed in percentage of weight; EE_i is ecotrophic efficiency which is the proportion of the ecological production consumed by predators and/or exported (Ricker, 1969) and EX_i is the export (i.e. catch) for any group (Christensen et al., 2008). $E_i + BA_i$ are terms for emigration and biomass accumulation, if occurring.

6.2.3 Data collection and grouping of biota into model compartments

The model for Lake Tono has 9 fish groups, 1 predatory bird group and 1 crocodile group. That of Lake Bontanga has 10 fish groups and 1 predatory bird group. The Golinga model has 11 fish groups. In addition to these groups, each of the three models has 2 invertebrate groups (insects plus larvae and zoobenthos), 1 zooplankton group, 2 primary producer groups (macrophytes and phytoplankton) and 1 detritus group. (Tables 6.2, 6.3 and 6.4).

6.2.4 **Input parameters**

6.2.4.1 **Biomass (B)**

Primary producers

Chlorophyll a was estimated *in situ* using a multi-parameter water quality probe (OTT Hydrolab DS5X) that was suspended at a depth of 2 m for 24 hours each month (July 2016-June 2017) and the data were logged at one-hour interval. The resulting estimates of mean annual chlorophyll a concentration (13.9, 17 and 26.1 mg/m^3 for Tono, Bontanga and Golinga, respectively) was then multiplied by the euphotic depth of the respective lake to obtain the water column values per unit area (/m^2). The euphotic depth was estimated from the Secchi depth transparency measurement (73, 49 and 38 cm, for Tono, Bontanga and Golinga, respectively) conducted from July 2016 to June 2017. These values were then converted to euphotic depth of 2.6, 1.7 and 1.3 m at Tono, Bontanga and Golinga, respectively using Holmes (1970) equation for turbid waters. Resulting chlorophyll a values for the three lakes of 36.1, 28.9 and 33.9 mg/m^2, respectively were converted into carbon using the factor of 1:40 - Chlorophyll a: Carbon (Brush et al., 2002) and then to weight with the conversion factor of 1:14.25-Carbon: wet weight (Brown et al., 1991). The resulting estimates for phytoplankton biomass were 20.6, 16.5 and 19.3 g WW/m^2 for Tono, Bontanga and Golinga, respectively (Tables 6.2, 6.3 and 6.4).

The biomass of aquatic macrophytes was estimated following the protocol of Finlayson et al. (2000). The aquatic macrophytes within the reservoirs were collected at four sampling stations: two each on the left and right banks of the reservoirs, respectively and in five replicates at each sampling point using 0.31 x 0.31 m quadrats, giving an area of 0.1 m^2. The macrophytes were sampled in August 2016 (the peak of the wet season) and April 2017 (the peak of the dry season). All above-ground plant material within the quadrats was removed by cutting, placed into plastic bags and returned to the field base. The plant material was initially sun-dried and then oven dried to a constant weight at 70ºC and weighed. The biomass of aquatic macrophytes was estimated as 51.34, 33.87 and 25.41 t km^{-2} for Tono, Bontanga and Golinga, respectively.

Detritus

The detritus biomass (D) was estimated using an empirical relationship that relates detritus biomass to primary productivity and euphotic depth (Christensen and Pauly (1993):

$$\log D = 0.954 \log PP + 0.863 \log E - 2.41 \qquad (2)$$

where D is the detritus biomass (g C/m^2), PP is the primary production (g C/m^2/year) and E is the euphotic depth (m). Since there were no prior estimates of gross primary production in the lakes, mean value of 0.86 g C/m^2/d was obtained from similar reservoir systems in the nearby Ivory Coast (Arfi et al., 2003). This equals a gross primary production of 312.53 g C/m2/yr. Using this value and the respective lake euphotic depth and converting them to wet weight resulted in a detritus biomass of 29.89, 21.19 and 17.01 g/m^2/yr for Tono, Bontanga and Golinga, respectively.

Zoobenthos

Biomass of zoobenthos (littoral fauna) mainly consisting of gastropods and bivalves was estimated from samples collected using a hand net with standardized sampling width of 0.25 m that was scooped across a length of 2 m and in the littoral zones of the reservoirs with depths not exceeding 0.5 m. The average biomass per swept area was then extrapolated to t km^{-2}. Since there was insufficient information on insects and larvae, the biomasses of these groups were estimated by the EwE program assuming an EE of 0.9 in all three lakes assuming these groups to represent important food items of several fish populations (Villanueva et al., 2006).

Zooplankton

Zooplankton samples were collected from July 2016 to June 2017 using a Hydrobios cylindro-conical net (acc. to Apstein, with mesh size of 55 µm, opening diameter of 25 cm and length of 100 cm) (Alhassan and Ofori-Danson (2017). The estimated zooplankton abundances were 1183, 1530, 2080 individuals/m^3 at Tono, Bontanga and Golinga, respectively. The total number of individuals was converted to wet mass using a conversion factor of 535 µg/C established for zooplankton in tropical reservoirs of West Africa (Aka et al., 2000). To obtain the zooplankton mass per area (m^2), the biomass (m^3) was multiplied by the mean depth of the respective reservoir, resulting in a biomass of 4.18, 4.83 and 3.0 t km^{-2} for Tono, Bontanga and Golinga, respectively. The zooplankton community in the reservoir was dominated by Copepods (*Thermocyclops* and *Nauplii*), Rotifers (*Keratella*, *Asplanchna* and *Trichocerca*) and Cladocerans (mainly *Penilia*).

Fish

For all the exploited non-target fish groups, biomass estimates were calculated from total annual yield and fisheries mortality (B= Y/F) assuming an exploitation rate of 0.5 (Rehren et al., 2018). From June 2016 to July 2017, fish landings were recorded for 5 consecutive days in each month and extrapolated to the monthly catch using an estimate of the average number of fishing days per month. Respective information was obtained from the fishers at the three reservoirs. The bulk weight of each fisher's catch per day was recorded and the caught fishes were then sorted into species groups, counted and weighed. At Tono, the 3 landing sites with the largest fisher populations (i.e., bays II, III, and IV, Fig. 6.1b and c) were monitored simultaneously for 3 days and bays I and V were monitored for the remaining 2 days. The two landing sites at Bontanga and the single landing site at Golinga were all monitored during the study period. Biomasses of the four commercially most important (in terms of landing volumes) species *Oreochromis niloticus*, *Sarotherondon galilaeus*, *Coptodon zillii* and *Auchenoglanis occidentalis* were based on estimates from length-based cohort analysis conducted for the species in all three lakes (Abobi et al., 2019a; Abobi et al., 2019b).

Predatory birds

Tono and Bontanga reservoirs are notable bird habitats. Birds on both reservoirs are dominated by White-faced Whistling Ducks *Dendrocygna viduata*. Between March and May 2017, we recorded an average population of 3400 and 1180 birds per day at Tono and Bontanga, respectively. The adults ducks weigh between 502-820 g (Del Hoyo et al., 1992). We used the average measured weight of 0.5 kg for all species and sizes. The biomass of predatory birds in Tono and Bontanga was then estimated as 0.091 and 0.088 t km^{-2}, respectively.

Crocodiles

Crocodile biomass was based on a study by Shirley et al. (2009), which surveyed the populations of crocodiles in Ghana and Côte d'Ivoire. *Crocodylus niloticus* was the most frequently encountered species and was found almost exclusively in northern, savannah woodland rivers and dams which include the Tono reservoir and its surrounding environment.

6.2.4.2 **Production/biomass (P/B)**

The P/B ratio under steady state conditions is equivalent to the total mortality rate (Z) for the fish groups (Allen, 1971). Therefore, the *Z* values estimated through a bootstrapped linearised length converted catch curve analysis were used for the four key species (Abobi et al., 2019a; Abobi et al., 2019b). For all other fish groups, Z or P/B values were taken from stock assessment studies conducted in reservoirs or from other similar reservoir ecosystems in the region. For zooplankton, insects and larvae, gastropods and bivalves (zoobenthos), macrophytes and phytoplankton, P/B values were taken from Lake Ayamé (Côte d'Ivoire;

Traore et al., 2008) and the Bagré reservoir in the nearby Burkina Faso (Villanueva et al., 2006) (Tables 6.2, 6.3 and 6.4).

6.2.4.3 **Consumption rates (Q/B)**

Consumption is the intake of food by a group over a defined time period (Christensen et al., 2000), which was entered as the ratio of specific consumption to biomass (Q/B ratio). The empirical equation of Palomares and Pauly (1998) was used to calculate Q/B values:

$$\log\left(\frac{\mathrm{Q}}{\mathrm{B}}\right) = 7.964 - 1.965T - 0.204\log W_{\infty} + 0.083A + 0.532h + 0.398d, (3)$$

where *T* is the water temperature, *W*∞ is the asymptotic body weight, h is the food type (0 for herbivores and 1 for predators) and *A* is the aspect ratio defined as *A* = h2/s, with h being the height of the caudal fin and s its surface area. W_{∞} was converted from L_{∞} values using the constant *a* and the slope *b* values from length-weight relationships. *L*∞, *a* and *b* values for *O. niloticus*, *S. galilaeus*, *C. zillii* and *A. occidentalis* were obtained from Abobi et al. (2019a) and Abobi et al. (2019b) (See Annex IV, Table S6.1). Data on aspect ratio was obtained from Fishbase (Froese and Pauly, 2019). For species that had unknown aspect ratio, the consumption/biomass (*Q*/*B*) ratios were taken from other models-Lake Ayamé (Côte d'Ivoire; Traore et al., 2008) and Bagré reservoir (Burkina Faso; Villanueva et al., 2006). For invertebrate groups, Q/B ratios were mainly obtained from other Ecopath models of similar systems.

6.2.4.4 **Diet composition**

Diet composition of predatory birds and crocodiles were derived from Villanueva et al. (2006). Stomach content studies provided references for the diet of *A. occidentalis* (Abobi et al., 2019b). At Golinga, the diet composition for *S. galilaeus* was based on Alhassan et al. (2011) and that of *C. zillii and Hemichromis spp* was based on Atindana et al. (2014). For all other fish species, information on diet composition were taken from Fishbase (Froese and Pauly, 2019) and from two other similar models in the region (Traore et al., 2008; Villanueva et al., 2006). The relative contribution of each group as prey for the respective group predating on them is shown in the Annex IV (Tables S6.2, S6.3 and S6.4).

6.2.4.5 **Fisheries yield (Y)**

Estimates of total annual catch for the target fish groups were based on field surveys as described in 2.4.1. Four main fishing methods are practised in the reservoirs and their respective contribution to the total catch (t km^{-2} yr^{-1}) is presented in Figure 6.6.

Table 6.2. Input parameters of the largest reservoir's (Tono) food web model. P/B, production per unit of biomass; Q/B, consumption per unit of biomass; EE, ecotrophic efficiency; and P/Q, production over consumption ratio of the different functional groups. Values calculated by EwE are presented in bold.

	Group name	Trophic Level	Biomass ($t\ km^{-2}$)	Catch ($t\ km^{-2}$)	P/B	Q/B	EE	P/Q
1	Predatory birds	**3.37**	0.091	-	0.25	63	**0.00**	**0.004**
2	Crocodiles	**3.58**	0.09	-	0.2	0.8	**0.00**	**0.250**
3	*C. gariepinus*	**3.06**	0.23	0.1154	3	9.75	**0.70**	**0.308**
4	*H. fasciatus*	**3.19**	0.235	0.117	4.14	13.44	**0.38**	**0.308**
5	*Mormyrus* spp.	**2.90**	0.04	0.020	0.97	8.03	**0.99**	**0.121**
6	*A. occidentalis*	**2.68**	3.12	0.391	0.73	13.82	**0.50**	**0.053**
7	Synodontis/Schilbe	**2.74**	0.68	0.34	1.83	14.94	**0.97**	**0.122**
8	*P. leonensis*	**2.91**	0.15	0.08	5.6	23.2	**0.91**	**0.241**
9	*O. niloticus*	**2.07**	6.03	2.796	1.74	39.1	**0.68**	**0.045**
10	*S. galilaeus*	**2.10**	9.33	5.541	2.99	48.9	**0.46**	**0.061**
11	*C. zillii*	**2.16**	3.87	0.665	1.94	44.6	**0.46**	**0.043**
12	Zooplankton	**2.05**	4.18	-	35	140	**0.79**	**0.250**
13	Insects and larvae	**2.08**	**12.61**	-	4	30	0.90	**0.133**
14	Zoobenthos	**2.03**	37.03	-	7	35	**0.22**	**0.200**
15	Phytoplankton	**1.00**	20.6	-	365.8	-	**0.23**	-
16	Macrophytes	**1.00**	51.34	-	5	-	**0.36**	-
17	Detritus	**1.00**	29.89	-	-	-	**0.16**	-

Table 6.3. Input parameters of the intermediate-sized reservoir's (Bontanga) food web model. P/B, production per unit of biomass; Q/B, consumption per unit of biomass; EE, ecotrophic efficiency; and P/Q, production over consumption ratio of the different functional groups. Values calculated by EwE are presented in bold.

	Group name	Trophic level	Biomass (t km^{-2})	Catch (t km^{-2})	P/B	Q/B	EE	P/Q
1	Predatory birds	**3.40**	0.088	-	0.25	63	**0.00**	**0.004**
2	*C. gariepinus*	**3.06**	2.92	1.458	1.08	9.75	**0.87**	**0.111**
3	*H. fasciatus*	**3.25**	0.38	0.188	4.14	13.44	**0.38**	**0.308**
4	*Mormyrids*	**2.90**	1.74	0.371	0.97	8.03	**0.62**	**0.121**
5	*A. occidentalis*	**2.66**	1.82	0.324	1.04	12.5	**0.67**	**0.083**
6	*B. nurse*	**2.55**	1.87	0.936	2.54	15.58	**0.77**	**0.163**
7	*Heterotis niloticus*	**2.85**	1.15	0.374	2.01	7.51	**0.78**	**0.268**
8	*P. leonensis*	**2.91**	0.53	0.267	5.6	22.7	**0.75**	**0.247**
9	*O. niloticus*	**2.07**	6.19	2.948	1.88	40.3	**0.77**	**0.047**
10	*S. galilaeus*	**2.10**	10.66	7.299	2.64	50	**0.67**	**0.053**
11	*C. zillii*	**2.16**	3.08	1.342	2.16	47	**0.44**	**0.046**
12	Zooplankton	**2.05**	4.83	-	35	140	**0.84**	**0.250**
13	Insects and larvae	**2.08**	**15.45**	-	4	30	0.90	**0.133**
14	Zoobenthos	**2.03**	67.41	-	7	35	**0.21**	**0.200**
15	Phytoplankton	**1.00**	16.5	-	365.8	-	**0.38**	-
16	Macrophytes	**1.00**	33.87	-	5	-	**0.52**	-
17	Detritus	**1.00**	21.19	-	-	-	**0.35**	-

Table 6.4. Input parameters of the smallest reservoir's (Golinga) food web model. P/B, production per unit of biomass; Q/B, consumption per unit of biomass; EE, ecotrophic efficiency; and P/Q, production over consumption ratio of the different functional groups. Values calculated by EwE are presented in bold.

	Group name	Trophic level	Biomass (t/km²)	Catch (t/km²)	P/B	Q/B	EE	P/Q
1	*Clarias gariepinus*	**3.08**	2.07	1.033	1.08	7.02	**0.65**	**0.154**
2	*Hemichromis spp.*	**3.19**	1.01	0.504	4.14	13.44	**0.20**	**0.308**
3	*Mormyrids*	**2.89**	1.93	0.966	0.97	8.03	**0.94**	**0.121**
4	*Heterotis niloticus*	**2.84**	1.63	0.815	2.01	7.51	**0.54**	**0.268**
5	*P. leonensis*	**2.90**	0.41	0.203	5.6	22.7	**0.92**	**0.247**
6	*Synodontis/Schilbe*	**2.81**	0.75	0.379	1.83	14.94	**0.69**	**0.122**
7	*B. nurse*	**2.55**	1.52	0.76	2.54	47.1	**0.79**	**0.054**
8	*Labeo spp.*	**2.12**	0.6	0.274	1.42	37.3	**0.95**	**0.038**
9	*S. galilaeus*	**2.07**	13.05	5.048	3.54	39.1	**0.38**	**0.091**
10	*O. niloticus*	**2.10**	16.52	6.903	2.03	48.81	**0.57**	**0.042**
11	*C. zillii*	**2.16**	0.45	0.227	2.37	44.77	**0.95**	**0.053**
12	Zooplankton	**2.01**	3	-	35	140	**1.00**	**0.250**
13	Insects and larvae	**2.08**	**17.02**	-	4	30	0.90	**0.133**
14	Zoobenthos	**2.03**	49.98	-	7	35	**0.35**	**0.200**
15	Phytoplankton	**1.00**	19.3	-	365.8	-	**0.33**	-
16	Macrophytes	**1.00**	25.41	-	5	-	**0.34**	-
17	Detritus	**1.00**	17.01	-	-	-	**0.25**	-

6.2.5 Balancing the models

The models balancing was guided by the values of the ecotrophic efficiency (EE) and gross efficiency (GE). The model parameters were calibrated to obtain for all the groups EE values < 1.0 and gross efficiency values (GE=P/Q) within 0.1 and 0.3 (Christensen and Pauly, 1992; Christensen et al., 2000; Christensen et al., 2008). For groups which had initial EE above 1, values of uncertain parameters were changed within a pre-established range of ±15% till the model was balanced as outlined in the Ecopath user's manual (Christensen et al., 2008).

6.2.6 Ecological and network indicators used to compare the models

The systems comparison follows Fath et al. (2019) who recently reviewed ecological network analysis metrics and suggested 7 as the most relevant ones to provide practical information for environmental decision-makers and stakeholders: (1) Average Path Length (APL), (2) Finn Cycling Index (FCI), (3) Mean Trophic level (MTL), (4) Detritivory to Herbivory ratio (D:H), (5) Keystoneness, (6) Structural Information (SI) and (7) Flow-based Information indices We concentrated on the first five of them and also used additional indices of ecosystem maturity such as total primary production/total biomass, net primary production/total respiration, total biomass/total system throughput, net primary production−total respiration) to compare the developmental state between the three lakes. According to Odum (1971), the ratio between total primary production and total system respiration (TPP/TR) would approach unity in mature system. TPP/TB ratio and NPPTR value tend to have low values in mature systems, whereas the ratio of biomass to total system throughput tend to increase as the system matures (Christensen, 1995).

The trophic aggregation routine (Lindeman, 1942) was used to: (1) calculate the efficiency of transfers within discrete trophic levels as the proportion of the flow entering a trophic level that is transferred to the next one (Christensen and Pauly, 1992) and (2) calculate the Detritivory to Herbivory ratio (D:H) (Fath et al., 2019) . We then compared the trophic structures and ecotrophic efficiencies of the 3 lake ecosystems and related them to age, lake morphology and environmental characteristics.

6.2.7 Mixed trophic impact (MTI)

The mixed trophic impact routine (Ulanowicz and Puccia, 1990) was used to: (1) evaluate the effect that a short-term increase in the biomass of a group will have on the biomass of the other groups in the ecosystem and (2) assess how a small increase in catch of one fishing gear impacts the catch of the other gears and the biomass of the functional groups.

6.2.8 Keystoneness index

Derived from the MTI routine, a keystoneness index (Libralato et al., 2006) was calculated to quantify the impact of each of the model groups on all other groups of the system relative to the group's biomass. A keystone group is a group that would significantly affect other groups even with a relatively small biomass. It is defined as:

$$\mathrm{KS_i} = \log\left[\varepsilon_i\,(1-\mathrm{p}_i)\right], \tag{4}$$

where KS_i is the keystoneness of group i, ε_i is the overall effect of group i, and p_i is the proportional biomass of group i. Functional groups that have a low biomass and a high overall effect are attributed high values of keystoneness (close or higher than zero).

6.2.9 **Data visualisation**

Figures 6.1, 6.3-6.6 and Annex IV, Figures S6.1-S6.4 were constructed in the R environment (R Core Team, 2019) using the packages *maps, mapdata, automap, marmap, ggplot2, shape* and *sp* for Fig. 6.1; and *ggplot2* for Figs. 6.3-6.6 and Annex IV, Figs. S6.1-S6.4.

6.3 Results

6.3.1 **Trophic relationships and structural analyses**

The relative importance of top predatory group (a group with TL>3) differed between the lakes: in Tono, these are crocodiles (TL=3.58), predatory birds (TL=3.37), *H. fasciatus* (TL=3.19) and *C. gariepinus* (TL=3.06). In Bontanga these are predatory birds (TL=3.40), *H. fasciatus* (TL=3.25) and *C. gariepinus* (TL=3.06), while in Golinga, *H. fasciatus* (TL=3.19) and *C. gariepinus* (TL=3.08) were the top predators (Tables 6.2, 6.3 and 6.4; Fig. 6.2). The top predators differed in biomass between the reservoirs. This holds particularly for *C. gariepinus* in Bontanga and Golinga where their biomasses were 13 and 9 times higher than in Tono (Tables 6.2, 6.3 and 6.4; and Fig. 6.2). Similarly, the biomass of *H. fasciatus* in Golinga was significantly higher than in Tono and Bontanga. The mean trophic level of the catch was 2.18, 2.3 and 2.31 (see Annex IV, Table S6.5) at Tono, Bontanga and Golinga, respectively. The estimated fisheries gross efficiencies for all reservoirs were low. They were estimated as 0.0013%, 0.0025% and 0.0024%, for Tono, Bontanga and Golinga, respectively (see Annex IV, Table S6.5). The proportion of fish biomass at TL I and II in Tono were almost the same, i.e. 48.08% and 47.72%, respectively, while the fish biomass in Bontanga and Golinga were concentrated at TL II with 65% and 64% (Table 6.5), respectively. In terms of fish catch distribution by trophic level, 83.8%, 73.5% and 72.5% of the catch from Tono, Bontanga and Golinga, respectively were obtained from TL II (Table 6.5). The lower catch from the higher TLs (≥III) in Tono explains why the catch has a lower mean trophic level than for Bontanga and Golinga.

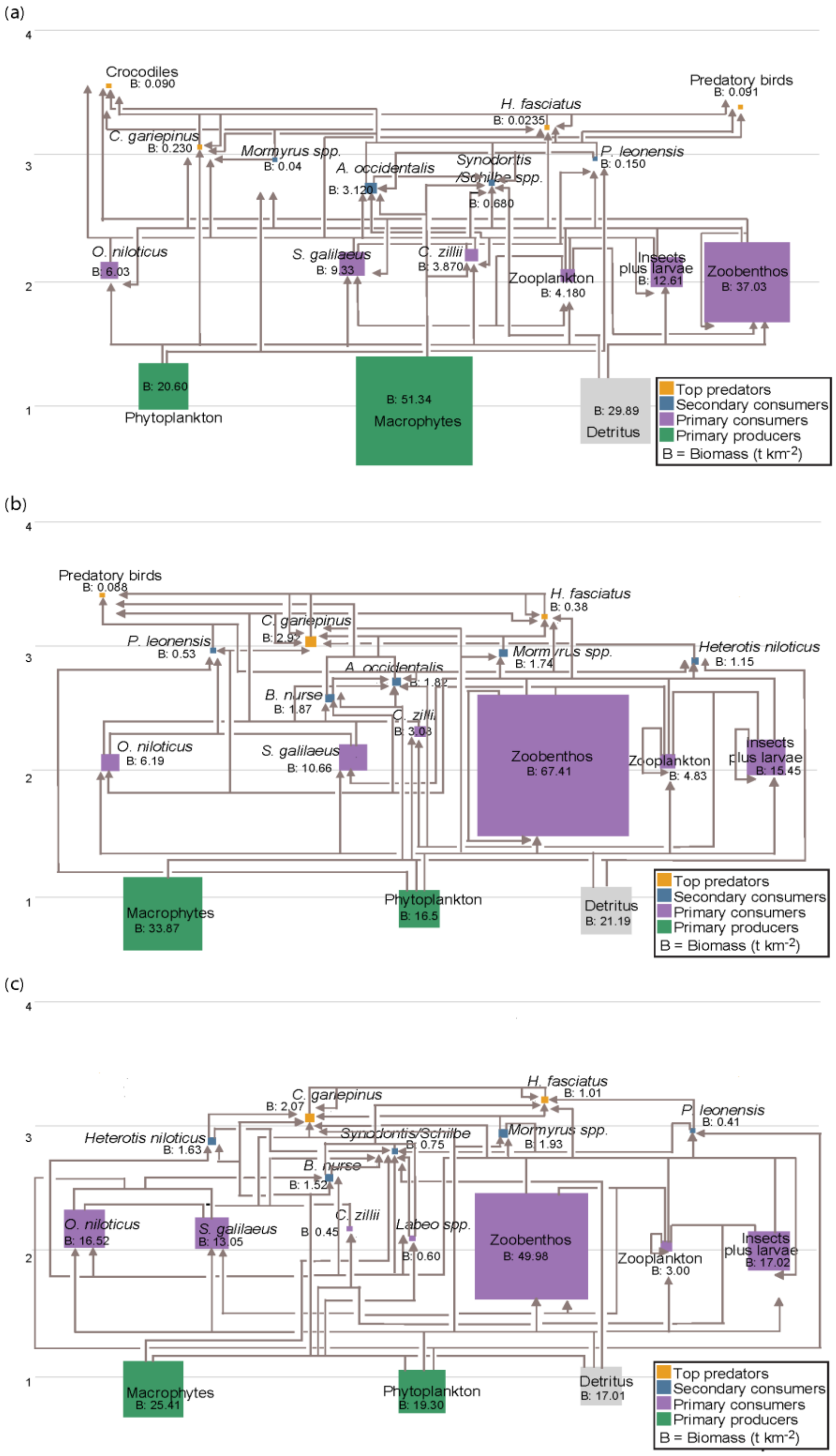

Figure 6.2. Food web diagrams (EwE output) of the reservoirs Tono (a), Bontanga (b) and Golinga (c) in Ghana. Box sizes are scaled proportional to functional group's biomasses (for exact values compare Tables 2-4) and the y-axis describes their trophic level (TL). Colours describe trophic groups: primary producers (TL = 1.0), primary consumers (TL 2.0–2.5), secondary consumers (TL 2.6–3.0), and top predators (TL > 3). For Ecopath input values please consider Tables 6.2, 6.3, 6.4 and Tables S6.1, S6.2, S6.3 and S6.4 in Annex IV.

Table 6.5. Distribution of catch (C- t km^{-2} yr^{-1}) and biomass (B- t km^{-2}) among the various trophic levels of Tono, Bontanga and Golinga reservoirs. Values obtained from *Flows and biomasses* under the Network Analysis routine of Ecopath output.

TL	Tono				Bontanga				Golinga			
	Catch		Biomass		Catch		Biomass		Catch		Biomass	
	t km^{-2} yr^{-1}	%	t km^{-2} yr^{-1}	%	t km^{-2} yr^{-1}	%	t km^{-2} yr^{-1}	%	t km^{-2} yr^{-1}	%	t km^{-2} yr^{-1}	%
1	0	0	71.9	48.1	0	0	46.6	28.3	0	0	44.7	28.9
2	8.4	83.8	71.4	47.7	11.4	73.5	106.7	64.8	12.4	72.5	98.4	63.6
3	1.6	15.4	5.9	4	3.8	24.4	10.6	6.5	4.3	25.1	10.7	6.9
4	0.08	0.8	0.33	0.22	0.31	2	0.79	0.48	0.39	2.3	0.79	0.51
5	0	0	0.01	0.01	0.016	0.1	0.039	0.02	0.02	0.1	0.04	0.03
Total	10.1	100	149.6	100	15.5	100	164.7	100	17.1	100	154.7	100

6.3.2 **Ecological indicators and network analyses**

The Average Path Length (APL), Finn Cycling Index (FCI) and Detritivory to Herbivory ratio (D: H) were all highest and lowest in the intermediate (Bontanga) and largest reservoir (Tono), respectively (Figs. 6.3 and 6.4; Annex IV, Table S6.5). The Mean Trophic Level of the Catch (MTLC) of Tono (2.18) was lower than Bontanga (2.30) and Golinga (2.31) (Fig. 6.3i and Fig. 6.4b; Annex IV, Table S6.5). The smallest reservoir (Golinga) had similar TST as the largest reservoir (Tono, being 30 times larger in surface area than Golinga) (Fig. 6.3a and Fig. 6.4i; Annex IV, Table S6.5). The medium-sized reservoir (Bontanga) had the lowest proportions of TST export and TST flow to detritus (Fig. 6.3b and e). The consumption flows of the largest reservoir (Tono) is nearly twice that of Bontanga (Fig. 6.3d), which is about 3 times smaller in surface area than Tono. The mean transfer efficiencies calculated were low for all reservoirs: 4.8%, 6.5% and 6.6% for the Tono, Bontanga and Golinga, respectively. The highest catch and the highest biomass per unit area were observed for Golinga (the smallest) and Bontanga (medium-sized) reservoirs, respectively, and the lowest catch and biomass per unit area values were calculated for Tono, the largest reservoir (Fig. 6.3k and o; Fig. 6.4a and e; Annex IV, Table S6.5).

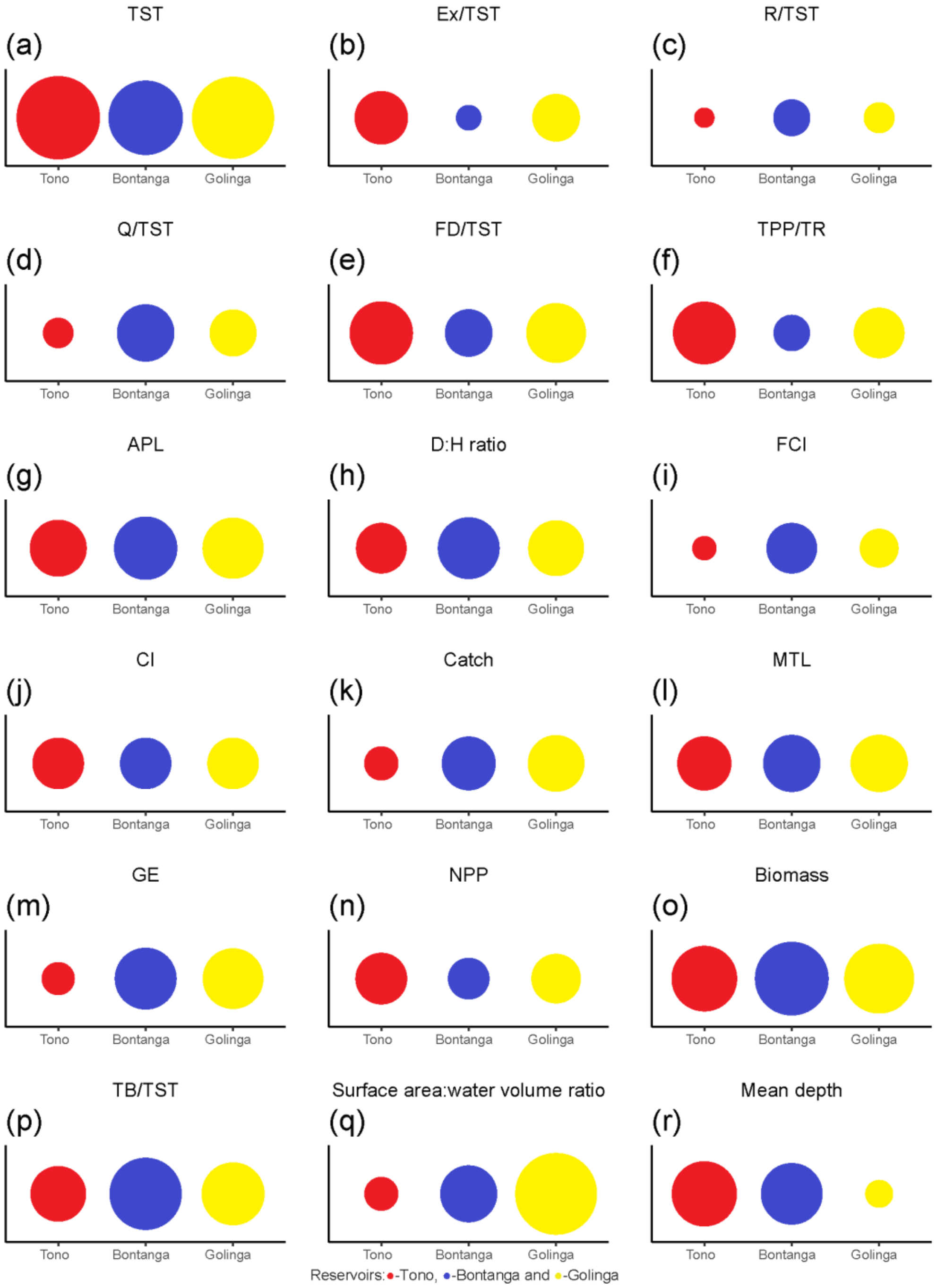

Figure 6.3. Comparison of system indicators of the three reservoirs (Tono in red, Bontanga in blue, Golinga in yellow). The sizes of the bubbles are comparable within each subplot. TST = total systems throughput, Ex/TST = export/ total systems throughput(proportion), R/TST = respiration/total systems throughput (proportion), Q/TST = consumption/total systems throughput (proportion), FD/TST = flow to detritus/total systems throughput (proportion), MTL = mean trophic level of the catch, TPP/TR = total primary production/total respiration, 1) APL = average path length, D:H=detritivory to herbivory ratio, FCI = Finn cycling index, CI = Connectance index, MTL = mean trophic level of the catch, GE = gross efficiency, NPP = net primary production, TB/TST = total biomass/total systems throughput. For exact values see Table S6.5 in Annex IV.

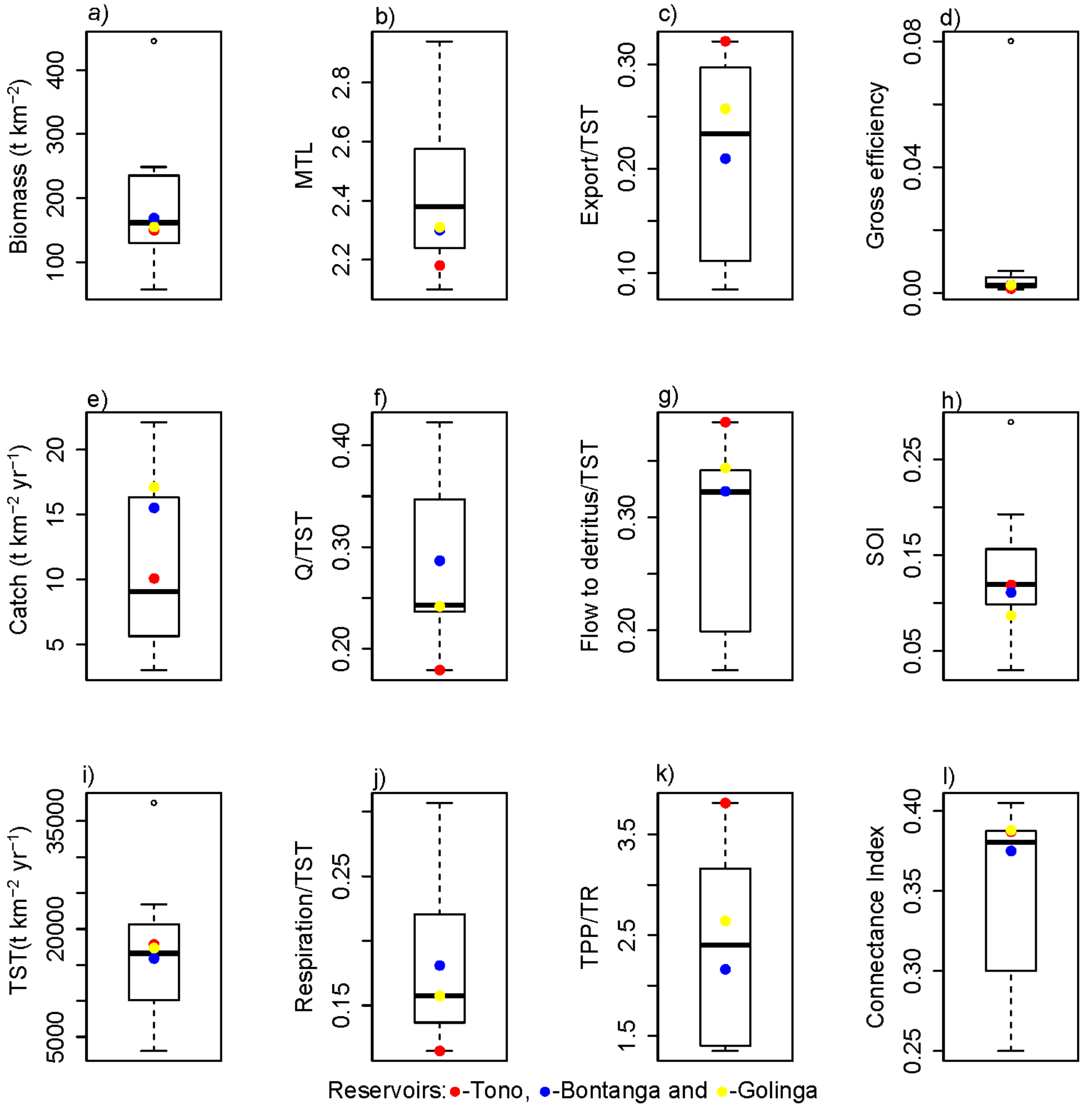

Figure 6.4. Results of ecological indicator calculation for the three studied reservoirs (Tono in red, Bontanga in blue, Golinga in yellow) in comparison to the range of values presented for similar lakes in literature: Ayamé, Côte d'Ivoire (Traore et al., 2008); Bagré, Burkina Faso (Villanueva et al., 2006); Koka, Ethiopia (Tesfaye and Wolff, 2018); Ubolratanad, Thailand, (Villanueva et al., 2008); Parakrama Samudrad Sri lanka (Villanueva et al., 2008); and Wyrae, India (Panikkar and Khan, 2008). The smallest observation (sample minimum), lower quartile, median, upper quartile, largest observation (sample maximum) and outliers are indicated in the boxplots. MTL = mean trophic level of the catch, TST = total systems throughput (proportion), Q/TST = consumption/total systems throughput (proportion), SOI = system omnivory index, TPP/TR = total primary production/total respiration. For exact values see Table S6.5 in Annex IV.

6.3.3 Mixed trophic impacts (MTI) and keystoneness

In Tono, an increase in predatory bird biomass would positively impact *Mormyrus spp.* and *Coptodon zillii* populations as the species' top predators, i.e. *H. fasciatus and C. gariepinus* are negatively impacted. The cichlids groups have negative impacts on themselves, reflecting a high within-group competition for resources. A slight increase in the biomass of insects will be beneficial to most fish groups in the three reservoirs. The insect and larvae group biomass increase would positively impact *Mormyrus spp., H. fasciatus, B. nurse and H. niloticus* biomasses in both Bontanga and Golinga, while in Tono, only *A. occidentalis* and *Mormyrus spp.* of the fish groups would be impacted positively. This highlights the relative importance of insects and larvae in the food web of the three ecosystems.

With regard to the keystoneness index (Libralato et al., 2006), the predatory birds' group ranks first in Tono, while phytoplankton occupies the 1st rank in both Bontanga and Golinga reservoirs. In Tono, the next ranks in keystoneness are occupied by phytoplankton and omnivorous fishes (Fig. 6.5A). In Bontanga, *C. zillii* (benthic herbivorous fish), *C. gariepinus* (carnivorous fish), insects and larvae and predatory birds were the next functional groups in order of decreasing keystoneness (Fig. 6.5B), while in Golinga, the next four functional groups of the keystoneness rank order were *Brycinus* nurse (small pelagic omnivorous fish), *H. niloticus* (omnivorous fish) and carnivorous fishes: *H. fasciatus* and *C. gariepinus* (Fig. 6.5C).

6.3.4 Differences in total catch and fisheries productivity among reservoirs

Species catch composition and catch per unit area differed among the reservoirs, with total catch per unit of area being highest for the small (17.11 t km^{-2} yr^{-1} in Golinga), lowest in the largest (10.07 t km^{-2} yr^{-1} in Tono) and intermediate in the medium-sized lake (15.51 t km^{-2} yr^{-1} in Bontanga; Fig. 6.6; and Annex IV, Table S6.5). The highest species catch of 5.54 and 7.30 t km^{-2} in Tono and Bontanga, respectively were from *S. galilaeus*, while *O. niloticus* catches (6.9 t km^{-2}) were the highest in the smallest reservoir (Golinga)-Table 6.2, Table 6.3 and Table 6.4.

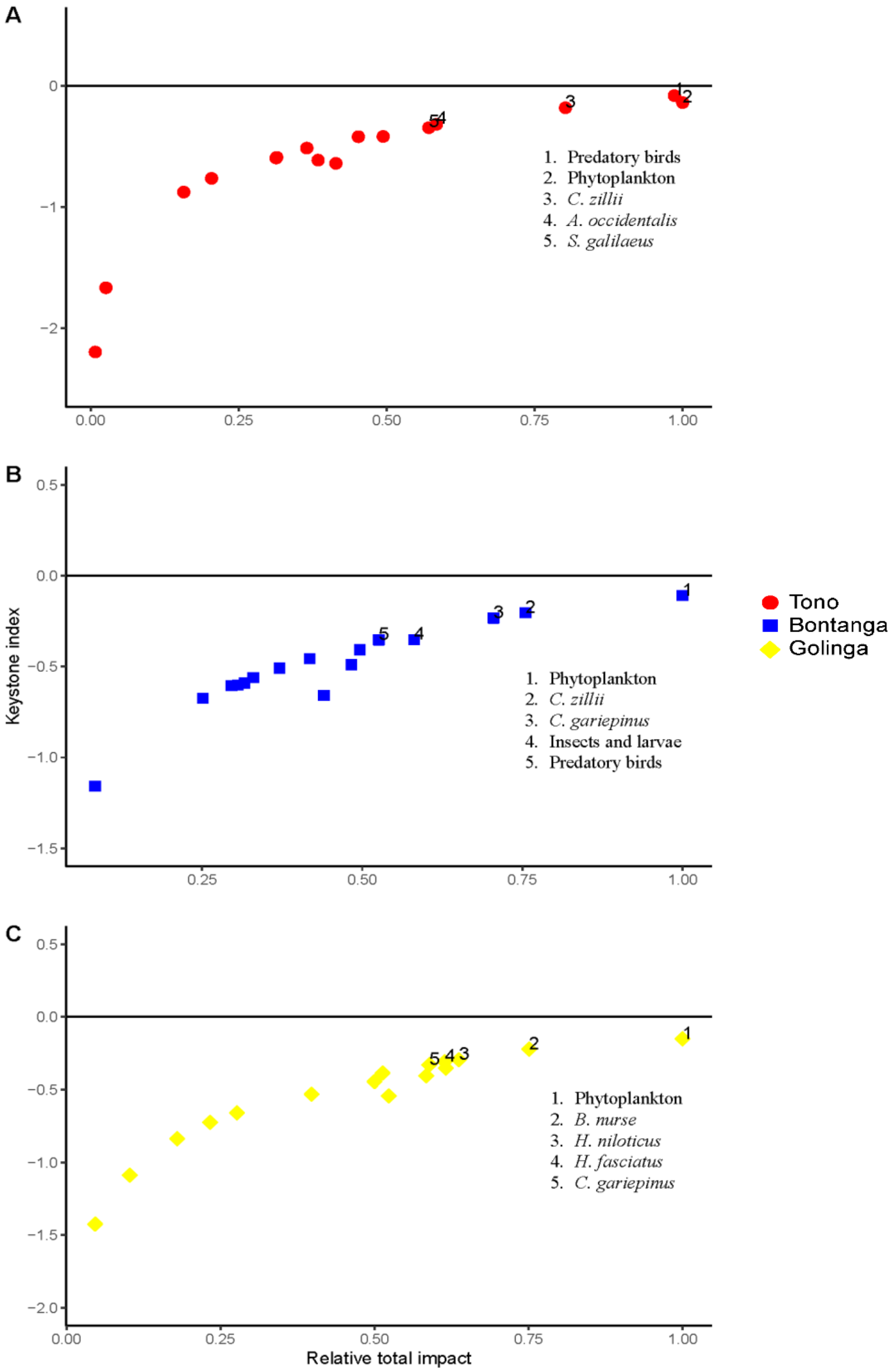

Figure 6.5. Keystoneness as calculated from EwE for the functional groups of the food webs of Tono (A), Bontanga (B) and Golinga (C) reservoir trophic webs. For each functional group, the keystoneness index (y axis) is reported against overall effect (x axis). Overall effects are relative to the maximum effect measured in each trophic web, thus for x axis the scale is always between 0 and 1. The species are ordered by decreasing keystoneness, and keystone functional groups are those exhibiting indices close to zero.

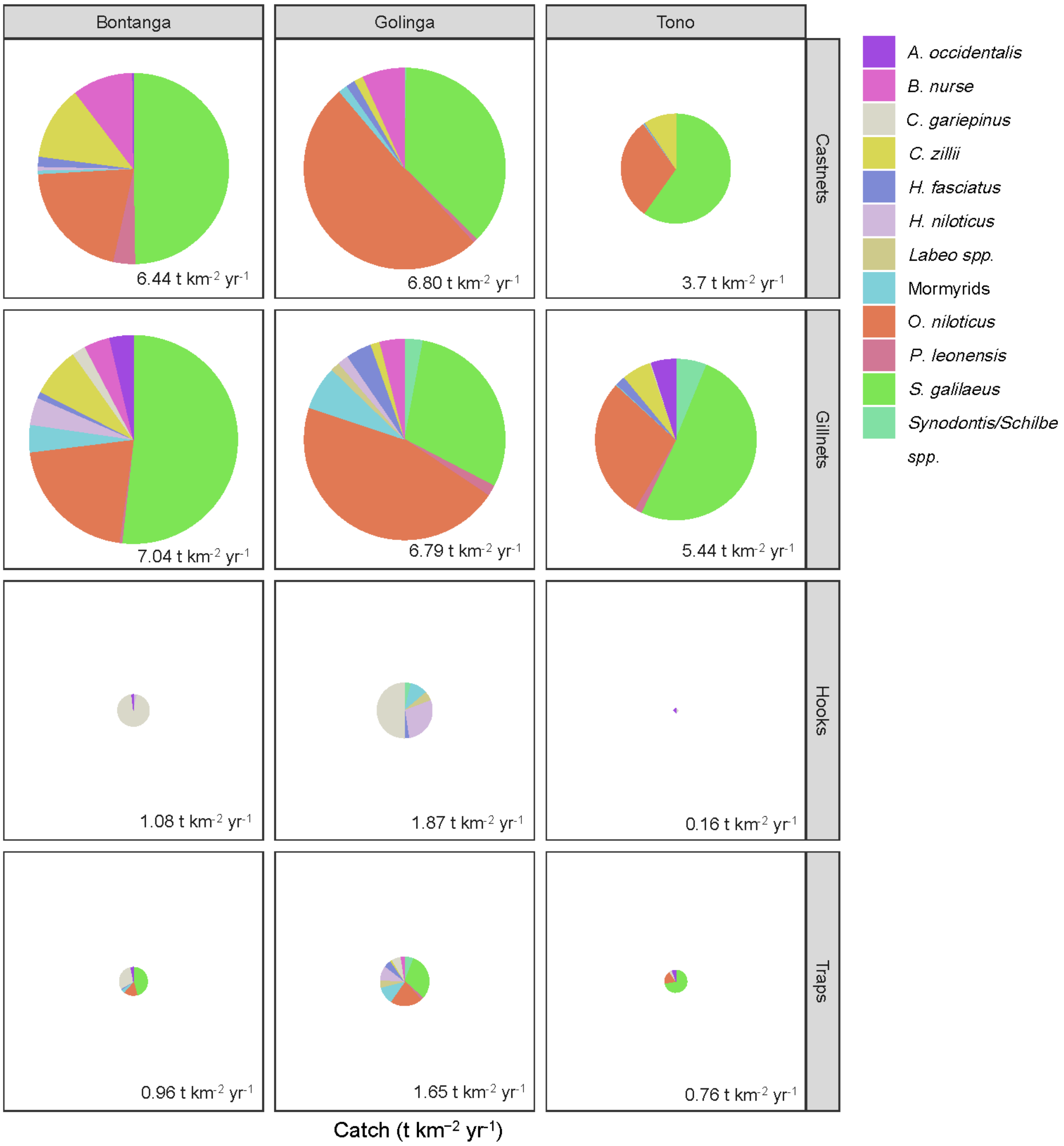

Figure 6.6. Total annual catch (t km^{-2} yr^{-1}) per fishing gear (castnets, gillnets, hooks and traps) targeting the fish groups in the three reservoirs (Tono, Bontanga and Golinga). The exploitation of the fisheries resources at the lakes was studied from July 2016 to June 2017. The size of the pie is proportional to the total catch per gear per lake, total values are also provided. For an overview of catch per trophic level see Table 6.5.

6.4 Discussion

Developing fisheries and improving productivity in lakes and reservoirs have been the focus of several West African states' ministries that are responsible for primary industries management. However, reservoirs in the semi-arid regions of Sub-Saharan Africa are threatened by climate change and expanding human populations. Natural river damming has been one of the main human interferences in natural ecosystems in the past 5000 years (Gubiani et al., 2011) and represents the principal way of creating an artificial lake. In Ghana, there are over 1000 dams, with 98% of them being small irrigational dams with individual surface areas not exceeding 5 km^2. Most of those are in northern Ghana, due to the particular aridness of the area. Apart from Akosombo and Bui dams of the Volta system in Ghana, which were constructed for electricity generation, all other dams were constructed mainly for agriculture irrigation purposes. Nevertheless, lakes and reservoirs are the main sources of inland fish production in Ghana. Understanding food web dynamics and ecosystem functioning of these important reservoir ecosystems is crucial for establishing meaningful ecosystem-based management strategies for sustaining local livelihoods.

6.4.1 **System differences**

After a reservoir is created, the fish community that establishes thereafter tends to be distinctive for each impoundment. This depends on many factors, amongst which are the geography and climate of the lake basin and its catchment, physical and chemical characteristics of its water mass, the composition of the original fish fauna of the basin and the presence or absence of introduced species (Guiral et al., 1999; Winemiller, 1995). But in spite of these attributes which are unique to each case, certain characteristics are common to all (Jackson et al., 1988), such as the principal structure of food webs being based on primary producers and benthic consumer groups.

Using the Ecopath modelling approach, differences in food web structures and resource productivities of the three man-made lakes Tono, Bontanga and Golinga were described and quantified. Results suggest that while all the fish species encountered during the study exist in Bontanga, six species (*Brycinus nurse, Citharinus citharinus, Distichodus engycehpalus, Malapterurus electricus, Polypterus endlicheri* and *Protopterus annectens*) are lacking in the Tono reservoir, whereas in Golinga, four species (*Auchenoglanis occidentalis, Citharinus citharinus, Distichodus engycehpalus* and *Protopterus annectens*) were not found. The species also differ in productivity levels between the different reservoirs and some functional groups occupy different trophic levels (TL) in each ecosystem, indicative for food web differences between the lakes (e.g. *Synodontis*/*Schilbe spp,* and *H. fasciatus*). As an example, the Nile Tilapia (*Oreochromis niloticus*) is twice more productive in Lake Golinga than in Tono and Bontanga, due to the species preference for shallow waters (FAO, 2009a). Tono, the deepest reservoir had the lowest mean trophic level of the catch due to its deep zones, which seem to serve as 'refuge habitats' for high-trophic-level fish species against fishing, whilst the medium-size and the smallest shallow reservoirs had more high-trophic-level fish species exposed to fishing.

The total fish biomass per unit area and the total annual catch per unit area were highest in the smallest (Golinga) and lowest in the largest (Tono) reservoir. The latter also had the lowest mean trophic level of the catch (Fig. 6.4b) reflecting the high contribution of low-trophic-level fish species (e.g. *O. niloticus, S. galilaeus* and *C. zillii*) and the absence of predatory species in the catches. The total fish biomass differ between Tono, Bontanga and Golinga (23.69, 30.34 and 39.94 t km^{-2}, but all values are within the reported range for other tropical African and Asian inland waters as such: lakes Koka (Tesfaye and Wolff, 2018), Bagré (Villanueva et al., 2006) and Parakrama Samudra (Panikkar and Khan, 2008), with 19.24, 22.63 and 54.7 t km^{-2} respectively.

According to Gubiani et al. (2011), Kolding and van Zwieten (2012), Tundisi (1993a) Tundisi (1993b), Tundisi (1988), Tundisi et al. (1993) and Tundisi (1990), the main drivers of lake ecosystem structure and function are: (1) morphometry/shape - the more dendritic a reservoir, the more complex is its morphometry, which introduces several components and increases spatial heterogeneity and variability, creating high biological diversity and gradients in physical and chemical state variables; (2) hydrological cycle and flow characteristics (Baijot et al., 1997) - Changes in water level lead to variations in volume, thus modifying niche availability and enhancing nutrient input during floods and (3) 'Evolution' or ageing - the characteristic of succession within a reservoir, with eutrophication having been considered as a major feature of ageing.

According to Post et al. (2000) ecosystem size, rather than resource availability, determines a food-chain length in natural lake ecosystems. This ecosystem-size hypothesis is based on the observed relationship between ecosystem size and species diversity, habitat availability and habitat heterogeneity (Cohen and Newman, 1991; Holt, 1993; Post et al., 2000). Gubiani et al. (2011) on the other hand, tested the relationship between age and maturity in 30 Neotropical reservoirs and concluded that maturity is an inherent characteristic of reservoir ageing, regardless of human interference, reservoir area or the number of species. This alludes to Odum's central theory of ecosystem development (Odum, 1969).

Among the system development indicators proposed by Fath et al. (2019), the Average Path Length (APL, Fig. 6.4g), Detritivory to Herbivory ratio (D: H, Fig. 6.4h) and Finn Cycling Index (FCI, Fig. 6.4i) were highest in Bontanga, the lake with intermediate age and the highest fish species diversity. Moreover, Bontanga was the lake with the lowest P/R ratio, the highest gross efficiency of the fishery and the lowest total primary production /total biomass ratio. All these descriptors suggest that Bontanga is the furthest developed of the three systems studied.

Comparing the P/R results of this study to a meta-analysis by Christensen and Pauly (1993), the intermediate-sized Bontanga appears to be close to a mature state, while Golinga (the smallest) in a developing and Tono (the largest) in an immature state (see also Annex IV, Table S6.5). The TST of the three systems were higher than those estimated for lakes Bagré in Burkina Faso (Villanueva et al., 2006), Koka in Ethiopia (Tesfaye and Wolff, 2018) and Ubolratana in Thailand (Villanueva et al., 2008), but were below the TST values of 23442.0 and 37497 reported from Parakrama in Sri lanka (Villanueva et al., 2008) and Wyra in India (Panikkar and Khan, 2008), respectively (Figs. 6.3a and 6.4i; and Annex IV, Table S6.5).

The largest reservoir (Tono) had the highest primary production (and highest biomass of both phytoplankton and macrophytes) among the three studied reservoirs, which could be related to nutrient loading from terrestrial sources. However, its fish biomass and catch per unit area (Fig. 6.4e, Fig. 6.6) was lowest, and the flow from primary producers to the detritus pool highest, which suggests that its primary production does not directly drive fish production at the higher trophic levels of this lake. A further explanation for the low catches may be that the fishery is unable to access the high trophic level species in the deeper more central part of the lake, which would confirm the general low exploitation rates calculated in this Lake (Abobi et al., 2019a). The smallest shallow reservoir (Golinga) had the highest concentrations of dissolved organic carbon and total dissolved nitrogen (See Annex IV, Fig. S6.2) due to high inputs of organic material from agricultural fields and the reservoir's shallow depth. This also supports the high total net primary production calculated for the reservoir.

Due to intense farming in the catchment area of the Tono reservoir, we expected higher nutrient concentrations in Tono than Bontanga, but the nutrient concentrations at the depth of 2 m were similar in both reservoirs (See Annex IV, Figs. S6.2 and S6.3). This could be due to (1) immediate and efficient uptake of nutrients transported to the Tono reservoir by primary producers in the water column as suggested by the high transparency of the lake (See Annex

IV, Fig. S6.1) and (2) storage of remaining nutrients in the sediments of the comparatively deep Tono reservoir resulting in minimal concentration in the upper water layers (i.e. at the sampling depth of 2 m).

Detritus has an important role in all three reservoir ecosystems studied, but its relative export in Bontanga is by about 6% lower than the export in Tono and Golinga, respectively (Fig. 6.3e and Fig. 6.4g). As a consequence, less detritus is accumulated and eutrophication is less severe. Though the Tono ecosystem had the highest biomass of macrophytic primary producers, the low transfer efficiency value (4.8%) observed is another reflection of the low coupling/energy transfer between the primary producers and the upper trophic levels. This is further supported by the low EE values estimated for the primary producer groups of this system (Table 6.2). Moreau et al. (2001) reported a similar low transfer efficiency of 4.65% in Parakrama Samudra reservoir in Sri Lanka attributing it to the inefficient use of primary production. The low transfer efficiency is also reflected in the fact that in Tono, predatory birds exert roles as high TL keystone species with an important top-down control of the food web.

Bontanga appears as the most mature and developed reservoir system based on the system indices calculated, and the overall high fish species diversity found here.

6.4.2 **Implications for resource management**

6.4.2.1 **Effects of water level fluctuations on fisheries productivity**

The findings on total fish catch per area support our stated hypothesis that the smallest reservoir (Golinga) is the most productive system (17.1 t km^{-2} fisheries landing; Fig. 4e), while it also has the highest intra annual fluctuation in surface area (52% reduction; Fig. 6.1h, Table 6.1). This confirms findings of Kolding et al. (2016), that the more the water level in the system fluctuates on a regular basis, the higher the average productivity. Similarly, shallow and small Africa lakes were described as the most productive (Fernando and Holčík (1982), with fisheries productivity generally declining with increasing lake size (Downing (2010). Further studies have shown that seasonal fluctuation in water level are associated with enhanced productivity (Junk et al., 1989; Kolding, 1993; Wantzen et al., 2008), and that small reservoirs can be richer in mineral concentrations than large artificial lakes, but less stable (in Burkina Faso; Baijot and Moreau (1997)). Kolding et al. (2016) reported increased phosphorous mobilization following wet–dry cycles owing to the alteration of physical, microbial and chemical processes in the aquatic terrestrial transition zone. However, there should be a sufficient amount of rainfall with associated run-offs to drive the nutrient enrichment of the reservoirs.

It is important to note that in years of high evaporation and little rainfall, too small reservoirs, while highly productive under "normal conditions", may lose a large part (if not all) of their fish productivity. This also means that trends in rainfall, evaporation and siltation can be crucial to the resilience and productivity of over 6000 small and shallow reservoirs in the region (Kolding et al., 2016). There are four main seasons that affect fishing in the lakes and reservoirs of northern Ghana: dry season (January to March; lowest water level), pre-wet season (April to June; water level rising), wet season (July to September; highest water level), and post wet-season (October to December; water level drawdown) (Abban et al., 2000).

Temperature and precipitation data from the Climate Change Knowledge Portal (CCKP, 2019) show differences of 0.44, 0.42, and 0.41°C in average monthly temperature in Tono, Bontanga and Golinga, respectively, when comparing the two periods 1961-1990 and 1991-2016. For the same period, monthly average rainfall decreased by 0.7 mm in Golinga and rose by 1.94 and 0.22 mm in Tono and Bontanga, respectively. However, according to predictions by the Environmental Protection Agency of Ghana (EPA, 2007), rainfall in the entire northern Ghana shall decline between 2.8% and 10.9% by 2050. Considering that Tono, Bontanga and Golinga, have surface area: water volume ratios of 0.20, 0.27, and 0.50, respectively, expected water shortage will be most severe in the smallest reservoir (Golinga). The larger, rounder and deeper lakes will thus be less affected.

These thoughts are aggravated by the apparent trend of surface area reduction of the studied reservoirs. For the smallest lake (Golinga), a surface area of 1.92 km^2 reported for the year 1998 (Obodai and Kwofie, 2001; Obodai et al., 2009) was reduced by 68% to 0.62 km^2 in the year 2016 (present work). Similarly, the intermediate-sized reservoir's (Bontanga) surface area reduced from 7.70 km^2 in 2001 (Kwarfo-Apegyah and Ofori-Danson, 2010; Obodai and Kwofie, 2001; Obodai et al., 2009) by 13% to 6.70 km^2 in 2017 (present work). Though no baseline value for the surface area of the largest reservoir (Tono) could be found in literature, the seasonal variations observed during our study period of 33% surface area reduction from wet to dry season (in 2017) indicate the potential magnitude of change.

Siltation (sediment loading) is perhaps the single most important factor that affects reservoir ecosystem size, causing a continuous reduction in overall surface area of the reservoir and mean depth. When combined with climatic drivers (i.e. unpredictable rainfall pattern and high evaporation) seasonal changes may become more drastic in the reservoirs affecting system resilience and stability. Especially when reservoirs reflect important socio-economic contributions to livelihoods of surrounding human communities, these dynamics should be carefully monitored and potential mitigation strategies developed.

6.4.2.2 **Impacts of human activities on reservoir ecosystems**

In addition to climatic-environmental dynamics, human activities within the catchment area of a reservoir affect the ecosystem functioning and together with fishing cause changes in fish species composition and size structure. A study by Adongo (2015) indicates that Tono and Golinga are the reservoirs with the highest number of farmers engaged in irrigated farming at the upstream of the reservoirs (139 farmers and a farmed area of 42 ha at Tono; 24 farmers and an area of 2.5 ha at Golinga and 11 farmers and an area of 1.2 ha at Bontanga). The number of people (km^{-2}) depending on the reservoirs is highest for the smallest lake (Golinga) and lowest for the intermediate-sized lake (Bontanga). Unregulated agriculture within catchment areas is a challenge that both Tono and Golinga are already facing. Around the smallest reservoir (Golinga), land preparation for crop cultivation and lack of erosion control likely contribute to the observed high turbidity and associated low water transparency during the dry and the pre-wet seasons (Annex IV, Fig. S6.1). Because there are no legal requirements for protection of buffer zones around rivers, waterbodies and wetlands, the desired minimum buffer width of 60-90 m recommended under the Riparian Buffer Zone Policy for Managing Freshwater Bodies in Ghana (Water Resources Commission, 2013) for protecting reservoir shoreline against degradation and potential future threats (like climate change) is not implemented.

Farming activities including ploughing of land, slash and burn, and animal grazing within the immediate width of the flood zone reduce lake-side vegetation, render the reservoir flood area bare, accelerate erosion and sediment transport. Consequently, the conversion of the reservoirs' buffer zones into croplands and grazing grounds contribute to the reduction in the overall surface area and the mean depth of the reservoir. In the area of the largest reservoir (Tono), the excessive use of fertiliser for crop production has been widely reported (Adazabra et al., 2013; Anim-Gyampo et al., 2013; Pelig-Ba, 2011). As a consequence, aquatic macrophytes develop excessively and affect water quality and fishing activity. This is supported by the results of Adongo (2015) who described clear distinctive conditions of the three reservoirs. Accordingly, Tono contains considerable amounts of sediments due to irrigated farming at the upstream of the reservoir and floods, Bontanga (the intermediate-sized reservoir) is in good condition, though it contains some amounts of sediments. Golinga (the smallest reservoir) is highly loaded with sediments and weeds and has an average siltation rate of 7.7 cm yr^{-1}. This lake is projected to be filled with 50% sediments in the year 2041, while this percentage is likely to be reached for the lakes Bontanga and Tono in the years 2123 and 2179, respectively (Adongo et al., 2019). This implies a potential loss in fisheries production due to aquatic habitats modification and/or removal and hence urgently requires intervention if fisheries productivity was sought to be maintained.

Considering the competing use of the reservoir's water for both irrigational farming and fisheries production, collaborative efforts are needed to form joint working committees to promote sustainable use of the reservoirs for both agriculture and fisheries production. At present two government ministries are responsible for food and agriculture (i.e. MoFA) and fisheries and aquaculture development (i.e. MoFAD). Moreover, there is the Ghana Irrigation Development Authority (GIDA), and the Irrigation Company of Upper Regions (ICOUR), which manages the Tono irrigation scheme on behalf of MoFA. And the respective District or the Municipal assemblies (Tono-Kassena Nankana Municipal Assembly, the Bontanga-Kumbungu District Assembly, and Golinga-Tolon District Assembly). Collaborative efforts of the above government institutions and authorities are accordingly needed.

6.4.3 **Conclusion**

The study presents a comparative analysis of the food web structures and fisheries productivity of three man-made reservoirs systems in northern Ghana (Tono, Bontanga and Golinga), which are essential for food security and livelihoods of the rural communities in the region. The fisheries are dominated by tilapiine species (*Sarotherodon galilaeus* and *Oreochromis niloticus*). The study reveals differences in lakes' morphometric features that generate differences in ecosystem functioning and fishing activity. Bontanga, which has intermediate characteristics (age, overall surface area, water volume, mean depth, water level fluctuation) and less farming activities in the reservoir's catchment area depicted the highest level of system maturity-showing the narrowest ratio of total primary production to total respiration. While fisheries productivity (per unit surface area), is inversely related to lake size, we conclude that the use of small reservoirs in populated semi-arid environments for both irrigational farming and fisheries production is unsustainable due to problems associated with seasonal water loss, siltation and aquatic habitat degradation.

We recommend that the states in semi-arid regions of Sub-Saharan Africa include an ecosystem-based fisheries perspective in the planning and construction of dams as to augment the agricultural benefits derived from reservoirs. Such addition is urgently needed in the face of predicted climate change impacts and potential food insecurity in the region. It should be noted that, without prior consideration of fisheries in the larger frame of the reservoir investment, any introduction or fisheries creation thereafter may not fit the ecosystem demands and the fisheries potential of the reservoir.

CHAPTER 7: General discussion and conclusions

The main objective of the thesis was to develop an understanding of how differences in reservoir morphometry and physicochemical characteristics influence ecosystem structures and fisheries productivity. This involved (1) reviewing and updating empirical models for reservoir harvest estimations, (2) relating morphometric characteristics of the reservoirs to fish production, (3) assessing the exploitation levels and stock status of the reservoirs' target species and (4) providing holistic description of the reservoirs' biological interactions through a food web modelling approach. The major findings of the different studies that constitute this thesis and their implications for the management of Tono, Bontanga and Golinga reservoirs as well as other similar reservoir systems are discussed below.

7.1 Reservoir fisheries productivity

To improve and update available models of harvest potential from reservoirs in Ghana, the Chapter Two of this thesis focused on a review of data from the FAO fisheries and Aquastat databases, and published articles and reports on West African reservoirs. Particular focus was given to their morphometric and environmental features in relation to fish catch. The analysis of fish catch-reservoir surface area relationships showed that fish catch per unit area decreases with the size of the reservoir. This confirms findings of Downing (2010) and Fernando and Holčík (1982), who also found fish productivity per unit area to generally decline with lake size. The authors attributed this to decreased rates of nutrient recycling to the euphotic layer in large lakes (Downing, 2010).

To have region-specific models for harvest estimation, our analysis was limited to West Africa, as potential geographic differences in resource productivities have been observed in other studies (Marten and Polovina, 1982; Welcomme and Bartley, 1998; Yamada and Ruttan, 1980).

Using a range of reservoir surface area values, our analysis of West African reservoirs predicted, on average, more than twice the fish production (16.3 t km^{-2} yr^{-1}) what a previous model by Crul (1992) had predicted (6.2 t km^{-2} yr^{-1}). We think that this difference in the estimates between the two models (model of Crul (1992) can be attributed to (1) higher current catches of the reservoirs in the region, due to restocking activities that were accelerated mainly in the 1990s (Ouedraogo, 2010) and (2) growth in human population, which has contributed to an increase in fishing pressure. The increase in fishing pressure has led to gear diversification and the optimization of fishing techniques, which have driven the increase in total harvest levels.

Our findings agree with studies by Bhukaswan (1980) and Gubiani et al. (2011), which showed that the catch obtained from a water body might greatly depend on the development of the fishery. Following this reasoning it appears that the difference in predictions between the previous model of Crul (1992) and our model could also be attributed to the geographical differences in the datasets used since the first model was constructed with datasets on lakes and reservoirs across Africa, while our model was limited to West African lakes only, a region, which is possibly more intensively fished.

As found before, surface area of a reservoir seems to be the most powerful predictor of the total catch in African reservoirs (Crul, 1992; Marshall, 1984; Youngs and Heimbuch, 1982). Youngs and Heimbuch (1982) demonstrated that 97% of the variation in lake fish catch was explained by three factors only: area, mean depth and total dissolved solids. Similarly, our study revealed that fisheries productivity was inversely correlated with both mean depth ($r = -0.49$) and surface area ($r = -0.32$), while there was no significant correlation with reservoir age ($r = 0.03$). The degree of water level fluctuations and discharge (FAO, 2016a; Kolding and van Zwieten, 2011) as well as total phosphorus levels (Hanson and Leggett, 1982) could also be useful predictors of fish yield. A multiple factor model should be applied once respective data for Western Africa are available

Analysis of the reservoirs' physicochemical characteristics (Chapter Three) showed that Chl-*a* concentrations of the reservoirs were similar during the wet, post-wet and pre-wet seasons, while during the dry season, concentrations were significantly different with Golinga recording the highest concentration of Chl-*a*, followed by Bontanga and Tono, respectively. The variation could be attributed to differences in organic matter inputs into the reservoirs. The high Chl-*a* contents in the Golinga reservoir during the dry season is reflected in the extreme and significantly higher turbidity levels recorded in the proceeding pre-wet (Apr-Jun; Figure 3.3a) season of high occurrence of algae and aquatic weeds (Asante et al., 2008). Considering the high levels of DOC, TDNb, NO2-N and turbidity, it is evident that this smallest and very shallow reservoir is more heavily impacted agriculture activities than the other two reservoirs. These results corroborate findings of Baijot et al. (1997), according to which smaller reservoirs are more productive and richer in mineral concentrations than large reservoirs, but are less stable due to seasonal water fluctuations.

There is increasing evidence that inland fish production in Africa may also largely dependent on external climatic drivers, such as seasonal variability of water levels (Gownaris et al., 2017; Jul-Larsen et al., 2003; Kolding et al., 2016; Kolding and van Zwieten, 2011, 2012), which agrees with our findings that monthly variation in reservoirs' fish catch was inversely correlated with the reservoirs water levels (Annex I, Figure S2.3). Considering the multiple uses of reservoirs in Ghana for community needs such as irrigation farming and fisheries, the resources are often subjected to severe competition. Therefore, in estimating reservoir fisheries production, the effects of water drawdown caused by irrigation should be considered, as intensive use of reservoir waters for farming reduces the size of the aquatic habitat available to fish production.

7.2 Exploitation and stock status of target species

In Chapters Four and Five of this thesis, the status of the target fish species in the reservoirs was evaluated by (1) reconstructing the catches using field data on landings and gillnet selectivity to estimate 'true' length frequencies using the Pasgear II software (Kolding and Skaalevik, 2010) and (2) applying a bootstrapping fish stock assessment (BFSA) approach (Mildenberger et al., 2017; Schwamborn et al., 2019) for the estimation of growth and mortality parameters, stock density and biological reference points. The correction of the length-frequency data for gear selection and raising it to represent the total catch of the system over the study period resulted in more robust and stable estimates of mortality. The BFSA approach made it possible to estimate the uncertainties around the life-history parameters and reference levels (e.g., $L\infty$, K, and $F_{0.1}$). Estimated values of exploitation rate (E) were compared with a reference value of 0.5, which has been proposed as an upper level of sustainable exploitation for fish species (Gulland, 1971). Additionally, length-based indicators (Cope and Punt, 2009; Froese, 2004) were included in the assessments and relative spawning stock ratios calculated for each target resource and reservoir as the second criterion of the current fishing state. The length-based indicators show whether a stock has spawning biomass above or below 40% of the unfished biomass.

The results showed that the cichlid species *Oreochromis niloticus*, *Sarotherondon galilaeus* and *Coptodon zillii* are heavily exploited in all three reservoirs. The estimated exploitation rates for the different species in the three reservoirs ranged from 0.23-0.66/yr (Table 4.5, Figure 4.5). In a previous study conducted in Bontanga by Ofori-Danson et al. (2008) it was found that the cichlid species were underexploited, whereas the results of this thesis suggested that *C. zillii* and *S. galilaeus* were optimally exploited (E<0.5), while *O. niloticus* was slightly overexploited (E>0.5). The shift from under- to over-exploitation for this species is likely explained by the increase in the number of active fishers by 57% in 2009 (Alhassan et al., 2014). In Tono and Golinga there were no baseline studies on the exploitation of the target species for comparison. Notwithstanding, the results from this study, which indicate a low fishing pressure, a report by Akongyuure et al. (2017a) indicated heavy fishing in Tono, through the intensive use of gillnets, cast nets and traps to target mainly large-sized tilapias. The high *Pmega* values (Table 4.7) calculated for the tilapias at Tono suggested that a large fraction of mature individuals (i.e. mega spawners) were available and targeted by the fishery in the reservoir and confirmed the market-driven size-selective fishery here.

Our calculated low exploitation rate (*E* = 0.24) and high spawning stock biomass (> 0.4 of unfished biomass) and stock biomass (3.12 t km^{-2}) of giraffe catfish (*Auchenoglanis occidentalis*) in the Tono reservoir suggest that the current fishing mortality is low in this reservoir and could be doubled to substantially increase yield. The situation differs in Bontanga, where the current exploitation rate was near the optimum level (*E* = 0.48) not allowing for a further increase in fishing effort. Since the proportion of immature individuals in the catches is high, a mesh size increase may be advisable to prevent long-term growth overfishing. The low fishing pressure and high fish biomass in Tono could be attributed to the low demand for fish around the Tono reservoir area. The Navrongo market, which is the closest to Tono reservoir, does not yet offer much smoked fish (the primary form of the species' commercialisation), compared with the Tamale market, which is supplied from Bontanga fish catches. These results show the effects of market preferences/demands around reservoirs areas on the fishing intensity and the need to linking any recommendations to increasing fishing mortality of the species in Tono reservoir to trade and supply links in Tamale and southern Ghana.

It is widely known that commercial fishing leads to changes in the size structure of the fished populations, so that simple length indicators of the fished population may be used to estimate the degree of exploitation (Arlinghaus et al., 2008; de Castro et al., 2015; Froese, 2004; Miranda and Dorr, 2000). While Berkeley et al. (2004) suggested that length compositions of caught fish should demonstrate the conservation of large and mature individuals, fishing patterns are common in many high-yielding small-scale inland fisheries in Africa, where the relative proportion of the fish community size structure is preserved through a balanced reduction of all species and size groups (Kolding et al., 2014; Kolding et al., 2015; Kolding et al., 2003; Kolding and van Zwieten, 2011; Misund et al., 2002). Therefore, considering the high *Pmega* values and overexploitation of the *C. zillii* and *O. niloticus* stocks in Tono Reservoir and the retention of immature fish by gillnets at Bontanga, a less selective fishing pattern is advised in both Tono and Bontanga reservoirs to prevent recruitment overfishing (i.e. fishing of too many spawners) and growth overfishing, respectively.

The exploitation rates, biological reference points, and LBI estimates all confirmed that the stocks in Bontanga reservoir are fully exploited, and without any scope for further increase in the fisheries. In Tono, all the fish stocks assessed (except for *A. occidentalis*, which seems underexploited) had E values, which indicated optimum (*S. galilaeus*) to slightly overexploited levels (*C. zillii* and *O. niloticus*), and the LBI estimates confirmed an uncritical and sustainable state for all the stocks in Tono reservoir. The exploitation rates of the fisheries resources in Golinga are low because fishers shift their effort from fishing to farming during the agriculture season. Although the E values suggested that the stocks in Golinga are in a healthy state, considering the LBI estimates, it is possible that, if a full-year fishing was adopted, the stocks may be driven above the optimum (E_{opt}=0.5).

7.3 Biodiversity and food web structures

In Chapter Six of this thesis, food web models were constructed to illustrate the interactions between the biological groups in each reservoir. Each model had the same number of compartments and (overlapping) functional groups to enhance model comparison and to reduce possible aggregation problems (Abarca-Arenas and Ulanowicz, 2002). To use the models for management advice, the input data were first qualified using the Pedigree routine available in EwE software version 6.6. From the relatively high average pedigree values of the three models estimated from all the input parameters (0.72, 0.79 and 0.68, for Tono, Bontanga and Golinga, respectively), an overall "good" quality of the models can be deduced (Christensen et al., 2008). This is due to the fact that most input data were obtained from in-situ sampling within the study period. The EwE food web modelling approach was used in this thesis to advance the knowledge of trophic interactions in tropical reservoirs and to contribute to the implementation of ecosystem-based management strategies in the three studied reservoirs, as demonstrated for other similar reservoir ecosystems in Table 1.1 of the thesis. Nilssen (1984) suggested that, when comparing tropical man-made lakes, all major morphometric characteristics and physical processes should be included. However, models of tropical lakes, which are more dynamic and perhaps also more complex compared to temperate ones, rarely have physical processes incorporated in their construction and analysis. Therefore, through its comparative approach, this thesis sought to demonstrate how differences in lake use patterns and lake physical features affect fisheries resource productivity.

In line with the fourth hypothesis of this thesis, Tono, Bontanga and Golinga were found to differ greatly in terms of morphology, water volumes, overall surface area, seasonal changes in water level and vegetation coverage, generating lake-specific conditions for fish growth and production. Bontanga, with average morphometric characteristics, differed from the other reservoirs by having a lower human population impact, a significantly lower P/R ratio, a higher TB/TST ratio, a higher FCI, a higher D:H ratio and the highest gross efficiency of the catch, all suggesting a more developed ecosystem.

Here, the highest fish species diversity was also found, which supports all the other descriptors, which indicate that Bontanga is the most developed of the three reservoir systems studied. While all the fish species found during the study exist in Bontanga, six species (*Brycinus nurse, Citharinus citharinus, Distichodus engycehpalus, Malapterurus electricus, Polypterus endlicheri* and *Protopterus annectens*) were lacking in the Tono reservoir, whereas in Golinga, four species (*Auchenoglanis occidentalis, Citharinus citharinus, Distichodus engycehpalus* and *Protopterus annectens*) were not found. Two tilapiine species (i.e. *Sarotherodon galilaeus* and *Oreochromis niloticus*) were found to be the mainstay of the reservoirs' fisheries. The highest fish catch and biomass per unit area was found for the shallowest and smallest lake (Golinga), while the lowest fish catch per unit area was found in the largest reservoir (Tono). These results agree with those of Chapters Two and Five and with the findings of Downing (2010) and Fernando and Holčík (1982) indicating high productivity of fisheries resources in small reservoirs (see also *section 7.2.*).

Due to excessive nutrient loading from allochthonous sources (high levels of DOC, TDNb, NO2-N in Golinga; and Silicate and Chl-*a* in Tono, as discussed in Chapters Three and Six of this thesis), plant biomass and primary production are high in Tono and Golinga. Since the utilisation of this primary production seems rather low, it contributes 86.8% and 81.1% to the detrital flow in Tono and Golinga, respectively. In Bontanga, to the contrary, less detritus is accumulated and eutrophication is less severe. In Tono, the low transfer efficiency value (4.8%) is a reflection of inefficient energy transfer between the primary producers and the upper trophic levels, which is also shown by the low EE values estimated for the primary producer groups of this system (Table 6.2). Moreau et al. (2001) reported a similar low transfer efficiency of 4.65% in Parakrama Samudra reservoir in Sri Lanka attributing it to the inefficient use of primary production. The low transfer efficiency is also reflected in the fact that in Tono, predatory birds exert roles as high TL keystone species (Figure 6.5A) with an important top-down control of the food web.

The findings of this thesis indicate that reservoir morphology, physicochemical characteristics and resource use patterns shape the food web structures and catch rates of man-made lakes. While the results of the thesis were consistent in indicating that small shallow reservoirs have higher fish production than large reservoirs, in populated semi-arid regions, small reservoirs appear largely unstable and vulnerable to seasonal water shortages when used for both irrigated agriculture and fishery production. In Chapter 3, it is also shown that small reservoirs are further challenged by high loads of sediments during the dry season water recession. The findings call for a critical evaluation of how different reservoir types, which are used for both primary industries (i.e. agriculture and fishery production) contribute to food security and livelihood opportunities in semi-arid regions of Sub-Saharan Africa.

7.4 Reservoir fisheries management and development

To manage reservoirs and associated riverine environments for the benefit of fish and fisheries, the status and contribution of reservoirs to capture fisheries production have to be evaluated and addressed. Furthermore, the technical criteria and measures germane to assessment frameworks need to be improved. For enhancing Ghana's fish production, development strategies should focus on fisheries and aquaculture production in rivers, floodplains, lakes, reservoirs, and brackish water systems. Research, policy and capacity building issues related to the development of these production systems must be addressed adequately. And, in order to fully exploit their potential, the management requirements of the individual systems need to be assessed and appropriate regimes implemented with stakeholders.

Reservoirs are rarely constructed for fishing per se. However, fisheries as a secondary purpose augment the benefits derived from these artificial systems. The following should be considered in creating an "optimal" reservoir for fishing: (1) The desired fishery should be developed from an ecosystem perspective-including the introduction of commercial species that are adequate in terms of production characteristics and ecosystem demands; (2) The reservoirs should be constructed with an appropriate size and depth that allows for adequate water spread and habitat diversity for the aquatic fauna. They should be large enough to withstand extreme periods of water loss due to droughts. Considering the projected severity of climate change impacts in the region and its associated high evaporation rate (1.5-2 m) and prolonged periods of droughts, a reservoir intended for both irrigation agriculture and fisheries should thus have a surface area of not less 2 km^2 and a mean depth of 4 m (3) Time for maximum filling and system development after construction needs to be taken into account, which very much relates to the size of the reservoir. During this process submerged vegetation need to decompose and soils and sediments need to settle. This is crucial as it has been noted that it may take decades or even centuries for most of the organic matter to decompose (McCully, 1996). A thorough clearing of vegetation in the submergence zone is needed before a reservoir is filled. This would allow the acceleration of the reservoir development and (4) Critical nutrient enrichment should be prevented. Under conditions of eutrophication tropical reservoirs may be colonised by aquatic weeds such as water hyacinth (*Eichhornia crasspipes*), which can cover water bodies entirely. While these aquatic macrophytes can function as shelter and substrate to young fish (Petrere, 1996), an excess growth and thick layers of aquatic plants may affect water quality and can negatively impact the life of fish species and other aquatic organisms as well as fishing activity (Figure 7.1). Regulating agriculture and livestock activities within the catchment area of the reservoirs will be needed to reduce the introduction of excessive organic matter input into the reservoirs. In principle, adequate light penetration and nutrient cycling in the reservoir will create optimal conditions for enhanced production (Figure 7.1). Controlling the submerged aquatic macrophytes of Tono reservoir will enhance the utilisation of primary production, and improve the reservoir water quality and fishing activity.

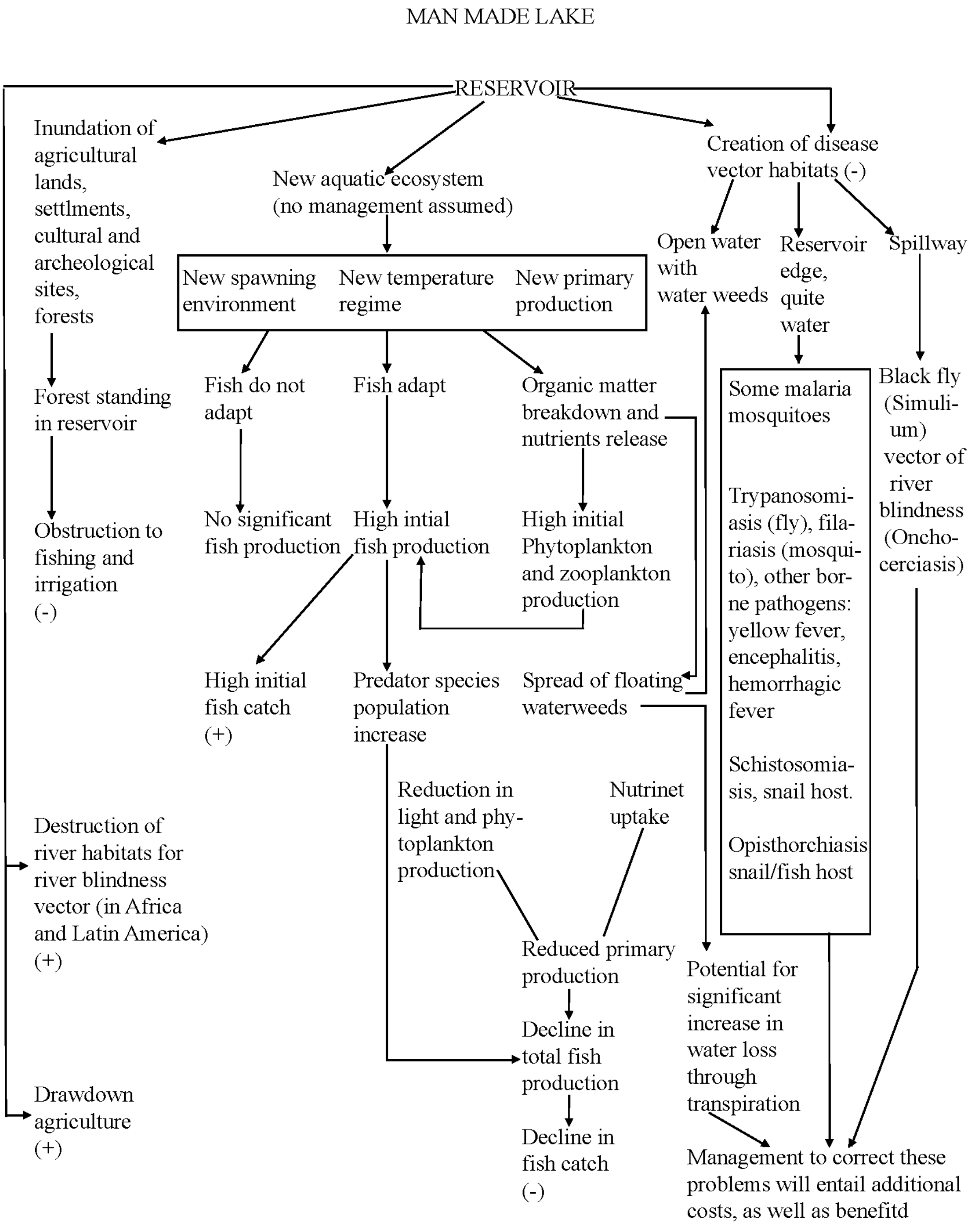

Figure 7.1. A simplified diagram showing the environmental consequences (Benefits (+) and Costs (-)) of a tropical river impoundment. Redrawn and modified from Freeman (1974) by Petr (1978).

Successful management of reservoir systems for fish production thus requires successful management of agriculture activities in the reservoirs' catchment areas to create a win-win situation for both fisheries and agriculture production. As shown in Figure 7.1, the benefits and negative consequences of river impoundment are associated with the development of fish communities in reservoirs. The drawdown of reservoir water is a benefit to agriculture production, while it reduces the size of the aquatic habitat available to fish production as discussed in *section 7.1.* Siltation is the most important factor that affects reservoir shape, size and turbidity. It results from excessive transport of sediments and silts from reservoirs catchment areas and has already reduced the surface areas of the studied reservoirs as discussed in *section 6.4.2.1.*

7.5 Conclusions and future prospects

The results of this thesis provided a detailed analysis of differences in reservoirs fisheries production and food web structures as related to their environmental and morphometric features. Fish production from reservoirs in West Africa has increased over the last two decades (as discussed in *section 2.4.2*). Our findings suggest that the use of the previous model by Crul (1992) leads to an underestimation of current fisheries production for West African reservoirs, while the model developed in this thesis is suitable for estimating fish catch from reservoirs of West Africa. As the fisheries of these reservoirs are largely unrecorded and undocumented, models of this thesis can be used to approximate their yield and to estimate their contribution to the total fisheries production of the region. The Tono, Bontanga and Golinga reservoirs vary greatly in morphometric features and physicochemical conditions. The results showed that Golinga was more significantly impacted by anthropogenic activities than the other two reservoirs with high concentrations of nutrients and a high amount of sediments.

The findings of this thesis showed that the reservoir fisheries are dominated by two tilapiine species (*Sarotherodon galilaeus and Oreochromis niloticus*). The target resources at Golinga can be sustainably exploited with the prevailing fishing pressure and pattern. Although in Bontanga there was no indication of overexploitation of the fishery resources, fishing pressure on immature *C. zillii* and *Auchenoglanis occidentalis* populations is high and may lead to recruitment overfishing if it is further increased. In Tono, the fishing pressure on large-sized *C. zillii* and *O. niloticus* populations should be reduced to avert recruitment overfishing. The giraffe catfish (*Auchenoglanis occidentalis*) fishery in Tono reservoir can be intensified by doubling the current fishing mortality to increase yield. Although higher stomach fullness of *Auchenoglanis occidentalis* was generally found in reservoir Tono, the bulk contribution of the food items of the species' populations from Reservoir Tono and Reservoir Bontanga did not differ significantly.

The food web models constructed in this study illustrate the trophic interactions in each reservoir. System indicators of the models were related to the reservoirs' physicochemical characteristics and human activities in the catchment areas. Bontanga, which has intermediate morphometric and environmental characteristics and less farming activities in the reservoir's catchment area depicted the highest level of system maturity and greatest fish diversity While fisheries productivity (per unit surface area), was shown to be inversely related to lake size, we conclude that the use of small reservoirs in populated semi-arid environments for both irrigational farming and fisheries production is unsustainable due to problems associated with seasonal water loss, siltation and aquatic habitat degradation.

Globally, inland fisheries (including those that operate in reservoirs) are constrained by lack of science-based understanding of how human activities affect the production potential of rivers and lakes (Cowx et al., 2010). Given the findings of this thesis, other similar reservoirs that are exposed to human activities should be adequately assessed and ecosystem-based management measures developed to sustain the contribution of reservoir fisheries to nutrition and food security, and to livelihoods. Future research should focus on (i) protecting and enhancing the physical environment of reservoirs for fish production, (2) maximising the sustainable yield of these reservoirs, and (3) the social-ecological resilience of reservoirs systems. These needs are crucial in the face of fast-growing demand for fish in Africa, Asia and the Pacific, where according to CGIAR (2017) a doubling or more of fish production in many countries will be needed by 2030.

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ANNEX

ANNEX I

Supplements for Chapter 2

Table S2.1. Difference between observed catch and Crul model estimate.

Country	Reservoir name	Surface area [km^2]	Total annual catch [tons/yr]	Crul's estimate	Difference %
Burkina Faso	Bagré	150	1040	787.4	24.3
Burkina Faso	Kompienga	150	1243	787.4	36.7
Cote D'ivore	Ayamé	180	1061	934.5	11.9
Cote D'ivore	Buyo	900	4345	4242.6	2.4
Cote D'ivore	Gboyo	0.07	4.442	0.6	86.9
Cote D'ivore	Katiali	0.24	4.082	1.9	54.6
Cote D'ivore	Korokara T	0.07	1.925	0.6	69.8
Cote D'ivore	Kossou	900	7000	4242.6	39.4
Cote D'ivore	Nambingué	0.1	1.825	0.8	55.4
Cote D'ivore	Sambakaha	0.15	7.572	1.2	84.3
Cote D'ivore	Taboo	34.6	70.67	198.3	
Cote D'ivore	Tiaplé	0.07	1.069	0.6	45.5
Cote D'ivore	Tiné	0.45	5.811	3.3	42.4
Ghana	Afife	5.5	70	35.2	49.7
Ghana	Barekese	6.4	80	40.6	49.3
Ghana	Bontanga	6.7	105.82	42.4	60.0
Ghana	Dawhenya	2.2	30	14.9	50.4
Ghana	Golinga	0.62	10.66	4.5	57.6
Ghana	Kpong	25.2	186.68	147.2	21.1
Ghana	Tono	18.6	187.2	110.7	40.9
Ghana	Vea	4.05	33.5	26.4	21.2
Ghana	Weija	37	420	211.2	49.7
Mail	Manantali	500	1500	2441.6	
Mail	Selingue	400	4000	1979.6	50.5
Nigeria	Asejire	23.69	1029	138.9	86.5
Nigeria	IITA	0.78	13.8	5.6	59.3
Nigeria	Kainji lake	1270	13361	5864.4	56.1
Nigeria	Kiri	115	2473	613.3	75.2
Nigeria	Shiroro	312	3489	1567.3	55.1
Senegal	Diama	235	4500	1200.7	73.3
Average					**50.3**

Table S2.2. Reservoir number by country in West Africa.

	Country	**Number of reservoirs**	**Source**
1	Benin	243	(Matsumoto, 2009)
2	Burkina Faso	1890*	(Cecchi et al., 2008)
		2100	(Halwart and Van Dam, 2006)
		1400	(Baijot et al., 1997)
3	Cape Verde	No data	
4	The Gambia	1u	(FAO, 2016b)
5	Ghana	1000*	(AgWater, 2011)
		808	(Barry et al., 2005; Liebe et al., 2005; Namara et al., 2011)
6	Guinea	22b	
7	Guinea-Bissau	No data	
8	Ivory Coast	500	(Aka et al., 2000)
9	Liberia	8	(FAO, 2016b)
10	Mali	800	(AgWater, 2011)
11	Mauritania	350	(AgWater, 2011)
12	Niger	1023*	(Halwart and Van Dam, 2006)
		31u	(FAO, 2016b)
13	Nigeria	937	(Odebiyi et al., 2013)
14	Senegal	5u	(FAO, 2016b)
15	Sierra Leone	8u	(FAO, 2016b)
16	Togo	6u	(FAO, 2016b)
	Total	6894	

[*] Data used in the estimation where a country had more than one record.

[u] The number may be underestimated

Table S2.3. Surface area of reservoirs in West Africa.

≠	Country	Reservoir name	Surface Area (km^2)	Source
1	Burkina Faso	Kompienga	150	(Vanden Bossche and Bernacsek, 1990b)
2	Burkina Faso	Bagré	150	(Vanden Bossche and Bernacsek, 1990b)
3	Cote D'ivore	Kossou	900	(Lévêque, 1999)
4	Cote D'ivore	Taboo	34.6	(Aliko et al., 2014)
5	Cote D'ivore	Buyo	900	(Van der Knaap, 1994)
6	Cote D'ivore	Ayamé	180	(Traore et al., 2008)
7	Ghana	Golinga	1.925	This study
8	Ghana	Kpong	25.2	(FAO, 2016b)
9	Ghana	Tono	18.6	(FAO, 2016b)
10	Ghana	Vea	4.05	(Adongo et al., 2014)
11	Ghana	Afife	5.5	(Vanden Bossche & Bernacsek 1990b)
12	Ghana	Weija	37	(Vanden Bossche and Bernacsek, 1990b);
13	Ghana	Barekese	6.4	(Vanden Bossche & Bernacsek 1990b);
14	Ghana	Dawhenya	2.2	(Vanden Bossche & Bernacsek 1990b)
15	Mail	Manantali	500	(Lévêque, 1999)
16	Mail	Selingue	400	(Lévêque, 1999)
17	Nigeria	Shiroro	312	(FAO, 2016b)
18	Nigeria	Asejire	23.69	(Ita et al., 1985)
19	Nigeria	Kiri	115	(Ita et al., 1985)
20	Ghana	Bontanga	6.7	This study
21	Senegal	Diama	235	(FAO 2016a)
22	Nigeria	IITA	0.78	(FAO 2016a)
23	Cote D'ivore	Tiné	0.45	(Gourdin, 1999)
24	Cote D'ivore	Katiali	0.24	(Gourdin, 1999)
25	Cote D'ivore	Sambakaha	0.15	(Gourdin, 1999)
26	Cote D'ivore	Gboyo	0.07	(Gourdin, 1999)
27	Cote D'ivore	Korokara T	0.07	(Gourdin, 1999)
28	Cote D'ivore	Nambingué	0.1	(Gourdin, 1999)
29	Cote D'ivore	Tiaplé	0.07	(Gourdin, 1999)
30	Nigeria	Kainji lake	1270	(Vanden Bossche & Bernacsek 1990b)
31	Ghana	Volta	8500	(Van Zwieten et al. 2011)
32	6862 small reservoirs (assumed area: 2 km^2 each)	Various	13724	
Total			27503.8	

Table S2.4. Productivity difference between Crul model (1992) and the model of this study.

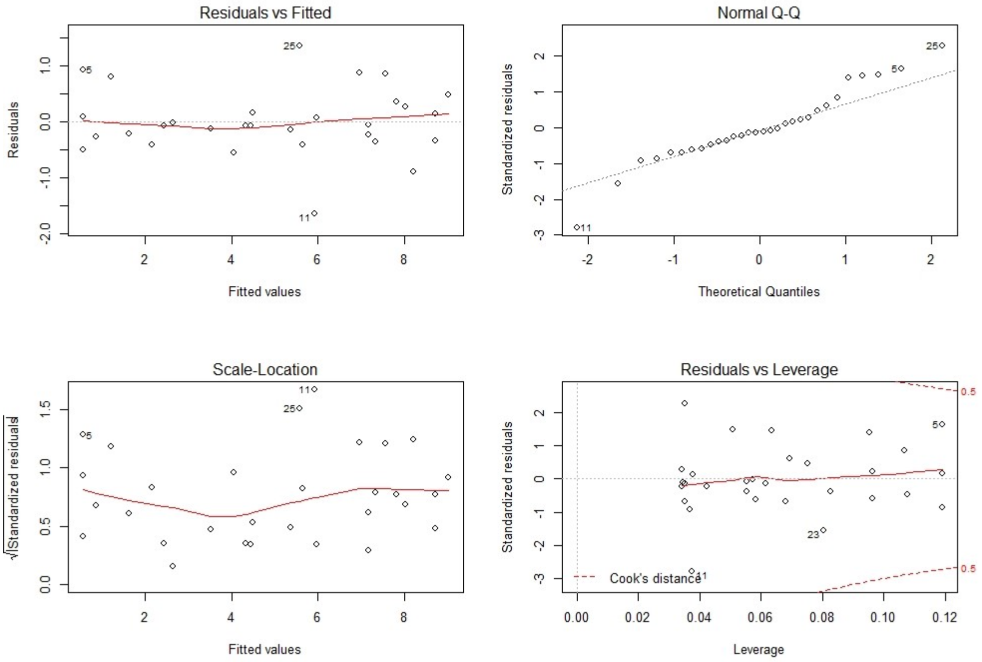
Reservoir surface area (km^2)	**Yield (tonnes/km^2/yr)**	
	Crul model	**This study (95% Cl)**
0.05	8.5	31.4 (20.1-49.1)
0.1	8.1	28.6 (19.0-42.8)
0.25	7.7	25.2 (17.7-35.8)
0.5	7.4	22.9 (16.7-31.4)
0.75	7.2	21.6 (16.1-29.1)
1	7.1	20.8 (15.7-27.7)
1.25	7.0	20.2 (15.3-26.6)
1.5	6.9	19.7 (15.1-25.7)
1.75	6.9	19.3 (14.8-25)
2	6.8	18.9 (14.6-24.5)
5	6.4	16.7 (13.2-21.1)
10	6.2	15.2 (12.1-19.0)
50	5.6	12.2 (9.5-15.6)
100	5.4	11.1 (8.4-14.5)
500	4.9	8.9 (6.2-12.6)
1000	4.7	8.1 (5.5-11.9)
2500	4.4	7.1 (4.6-11.1)
5000	4.3	6.5 (4-10.5)
7500	4.2	6.1 (3.7-10.2)
10000	4.1	5.9 (3.4-10.0)
Mean	**6.2**	**16.3 (11.8-22.7)**

Figure S2.1. Model one summary and residuals.

I. Model one summary

```
# > summary(CatchAreaModel)
#
# Call:
#   lm(formula = lnCatch ~ lnArea)
#
# Residuals:
#   Min       1Q   Median       3Q      Max
# -1.65194 -0.32428 -0.07332  0.24662  1.35312
#
# Coefficients:
#              Estimate Std. Error t value Pr(>|t|)
# (Intercept)   2.8532     0.1389   20.54   <2e-16 ***
#   lnArea      0.8626     0.0347   24.86   <2e-16 ***
#   ---
#   Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
#
# Residual standard error: 0.6037 on 28 degrees of freedom
# Multiple R-squared:  0.9566,  Adjusted R-squared:  0.9551
# F-statistic: 617.8 on 1 and 28 DF,  p-value: < 2.2e-16
```

II. Residuals of plot of the model one



III. Normality test of residuals of model one

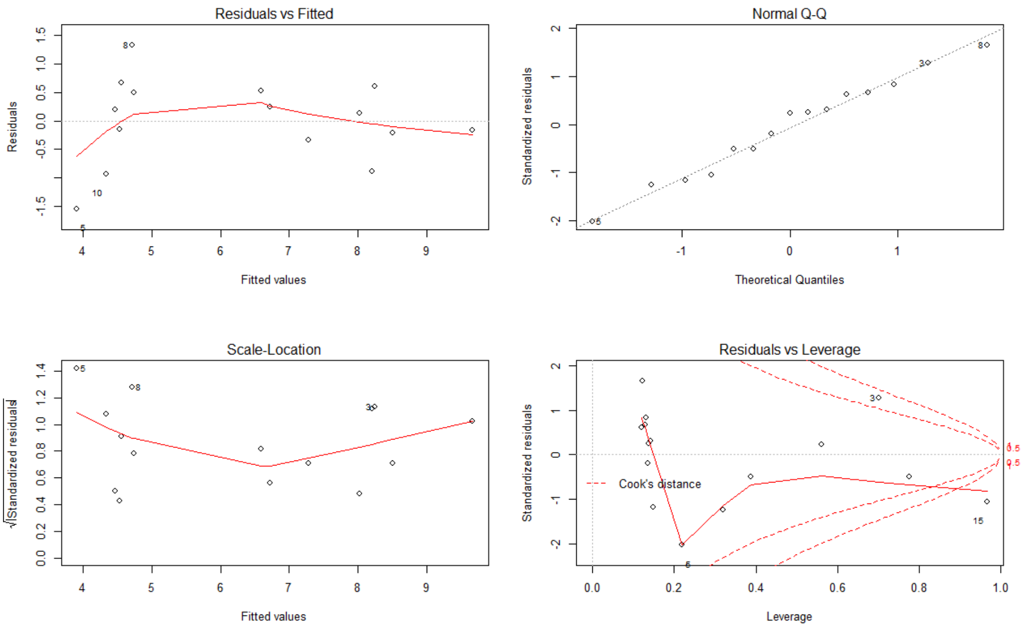
1. Anderson-Darling normality test: A = 0.64644, p-value = 0.0829
2. Cramer-von Mises normality test: W = 0.10877, p-value = 0.08057

Figure S2.2. Model two summary and residuals.

I. Model two summary

```
# > summary(AreaDepthModel)
#
# Call:
#   lm(formula = log(catch) ~ area + depth + I(area^2) + area:depth)
#
# Residuals:
#   Min       1Q  Median      3Q     Max
# -1.5449 -0.2723  0.1309  0.5165  1.3324
#
# Coefficients:
#                 Estimate Std. Error t value Pr(>|t|)
# (Intercept)    3.501e+00  5.160e-01   6.784 4.84e-05 ***
#   area         1.486e-02  3.394e-03   4.379  0.00138 **
#   depth        1.490e-01  5.930e-02   2.513  0.03075 *
#   I(area^2)   -5.120e-06  2.167e-06  -2.362  0.03980 *
#   area:depth  -4.363e-04  1.656e-04  -2.634  0.02497 *
#   ---
#   Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1
#
# Residual standard error: 0.8655 on 10 degrees of freedom
# Multiple R-squared:  0.8738,   Adjusted R-squared:  0.8233
# F-statistic: 17.31 on 4 and 10 DF,  p-value: 0.000172
```

II. Residuals of plot of model two



III. Normality test of residuals of model two

1. Anderson-Darling normality test: A = 0.27637, p-value = 0.6034
2. Cramer-von Mises normality test: W = 0.044076, p-value = 0.5806

Figure S2.3. Monthly variation in fish catch and water level at Tono (A), Bontanga (B) and Golinga (C). The bars in blue represent catch in tonnes (i.e. left y-axis) and the lines in red indicate water level in meters (i.e. right y-axis).

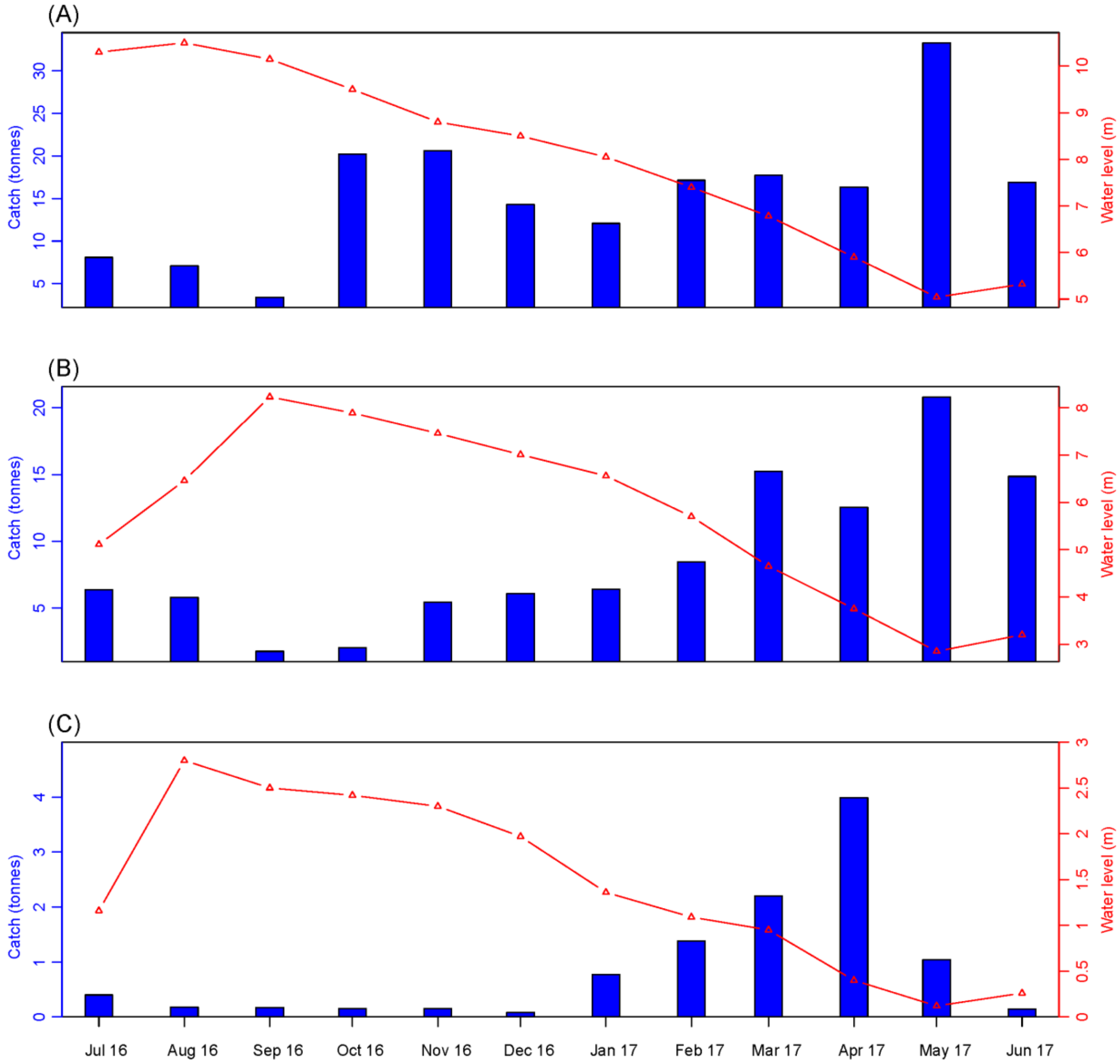


Figure S2.4. Comparison of the ln- transformed catch-area model fits for reservoirs with surface areas above and below 2 km^2

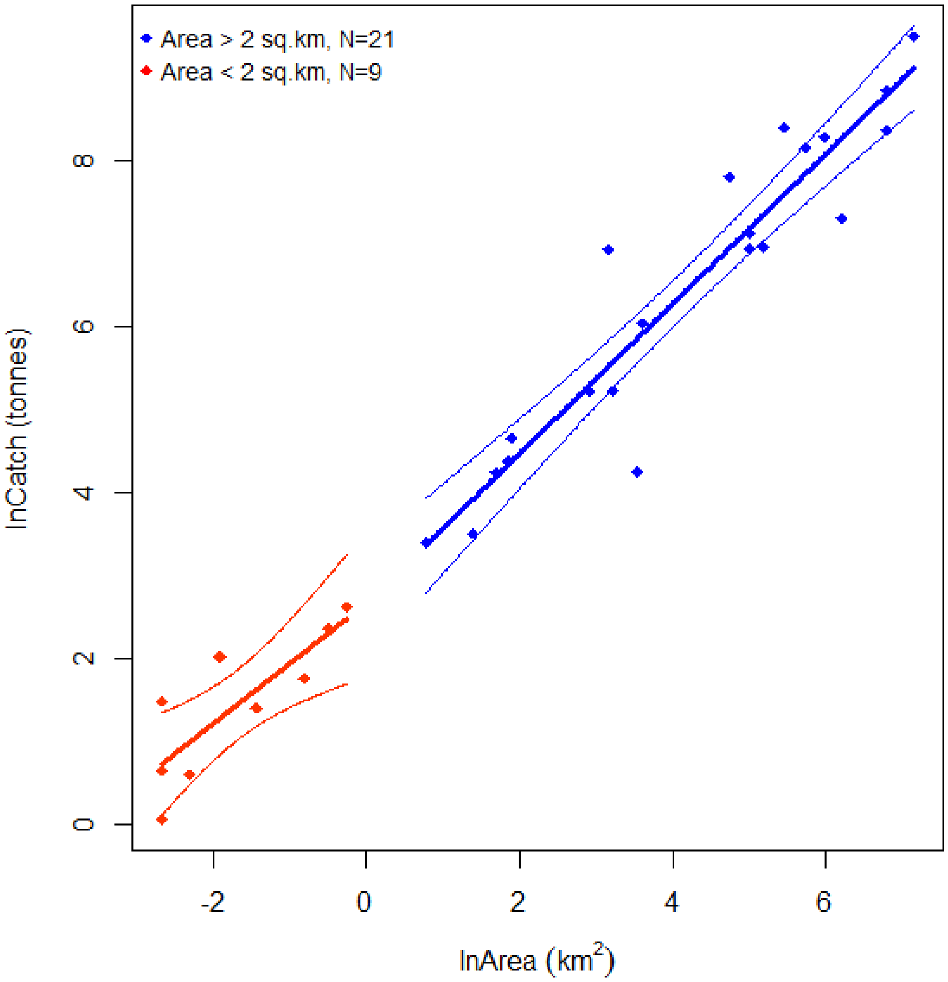


Figure S2.5. Analysis of covariance.

```
# > CatchAreaModel<-lm(lnCatch~lnArea*Size,data =fdata)
# > Anova(CatchAreaModel)
# Anova Table (Type II tests)
#
# Response: lnCatch
# Sum Sq Df  F value   Pr(>F)
# lnArea      66.748  1 175.2319 4.62e-13 ***
#   Size          0.077  1   0.2019   0.6569
# lnArea:Size  0.225  1   0.5895   0.4495
# Residuals    9.904 26
# ---
#   Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1
# > summary.lm(CatchAreaModel)
#
# Call:
#   lm(formula = lnCatch ~ lnArea * Size, data = pon.reg.)
#
# Residuals:
#   Min      1Q  Median      3Q     Max
# -1.6069 -0.3426  0.0350  0.2651  1.4140
#
# Coefficients:
#   Estimate Std. Error t value Pr(>|t|)
# (Intercept)   2.659907   0.324827   8.189 1.14e-08 ***
#   lnArea        0.904386   0.070347  12.856 8.97e-13 ***
#   SizeB         0.002421   0.537226   0.005    0.996
# lnArea:SizeB -0.179671   0.234016  -0.768    0.450
# ---
#   Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1
#
# Residual standard error: 0.6172 on 26 degrees of freedom
# Multiple R-squared:  0.9579,  Adjusted R-squared:  0.9531
# F-statistic: 197.3 on 3 and 26 DF,  p-value: < 2.2e-16
```

Figure S2.6. Comparison of models estimates.

```
# > ##Porductivity estimates analyesd for these areas (km2)=0.05,0.1,0.25,0.5,
              0.75,1,1.25,1.5,1.75,2,5,10,50,100,500,1000,2500,5000,7500,10000
#   > ## Esimates of productivity (tonnes/km2) by the two models
#   > Crul=c(8.5,8.1,7.7,7.4,7.2,7.1,7.0,6.9,6.9,6.8,
              6.4,6.2,5.6,5.4,4.9,4.7,4.4,4.3,4.2,4.1)
# > Study=c(31.4,28.6,25.2,22.9,21.6,20.8,20.2,19.7,19.3,
         18.9,16.7,15.2,12.2,11.1,8.9,8.1,7.1,6.5,6.1,5.9)
# > t.test(Crul,Study,var.equal = TRUE)
#
# Two Sample t-test
#
# data:  Crul and Study
# t = -5.7252, df = 38, p-value = 1.356e-06
# alternative hypothesis: true difference in means is not equal to 0
# 95 percent confidence interval:
#   -13.711895  -6.548105
# sample estimates:
#   mean of x mean of y
# 6.19     16.32
```

ANNEX II

Supplements for Chapter 4

Table S4.1. Raising factor for length frequency adjustment to total monthly catch for *Coptodon zillii, Oreochromis niloticus* and *Sarotherodon galilaeus* measured at Bontanga (Bon), Tono (Ton) and Golinga (Gol) reservoirs from July 2016 to July 2017. Lfq No. and Lfq catch refer to the number and the weight of the individuals measured respectively.

Reservoir	Species	Month	Lfq No.	Lfq catch (kg)	Total catch (kg)	Raise factor
Bon	*C. zillii*	Jul-16				
Bon	*C. zillii*	Aug-16	238	3.73	705.9	189.4
Bon	*C. zillii*	Sep-16	240	3.74	142.8	38.2
Bon	*C. zillii*	Oct-16	239	2.61	137.5	52.7
Bon	*C. zillii*	Nov-16	245	2.8	211.5	75.6
Bon	*C. zillii*	Dec-16	238	3.23	362.3	112.1
Bon	*C. zillii*	Jan-17	200	3.17	330	104
Bon	*C. zillii*	Feb-17	200	3.86	971.9	251.8
Bon	*C. zillii*	Mar-17	200	4.12	2063.6	501.3
Bon	*C. zillii*	Apr-17	193	4.56	1763.8	387
Bon	*C. zillii*	May-17	200	3.58	1889.8	527.5
Bon	*C. zillii*	Jun-17	200	5.19	345.4	66.6
Bon	*O. niloticus*	Jul-16	287	12.81	2123.2	165.8
Bon	*O. niloticus*	Aug-16	238	9.97	2721.8	272.9
Bon	*O. niloticus*	Sep-16	235	10.98	380.9	34.7
Bon	*O. niloticus*	Oct-16	238	8.26	617.1	74.7
Bon	*O. niloticus*	Nov-16	239	8.82	598.9	67.9
Bon	*O. niloticus*	Dec-16	241	13.03	1905.1	146.2
Bon	*O. niloticus*	Jan-17	200	9.03	649.3	71.9
Bon	*O. niloticus*	Feb-17	200	6.68	1063.5	159.2
Bon	*O. niloticus*	Mar-17	200	6.07	2539.7	418.5
Bon	*O. niloticus*	Apr-17	200	7.31	1634.2	223.7
Bon	*O. niloticus*	May-17	200	7.19	3358.5	467.2
Bon	*O. niloticus*	Jun-17	200	11.31	2161.6	191.1
Bon	*S. galilaeus*	Jul-16	240	4.69	3372.2	719.6
Bon	*S. galilaeus*	Aug-16	240	6.49	1604.9	247.2
Bon	*S. galilaeus*	Sep-16	280	8.83	500.5	56.7
Bon	*S. galilaeus*	Oct-16	240	8.31	879.6	105.9
Bon	*S. galilaeus*	Nov-16	238	8.19	1415.8	172.9
Bon	*S. galilaeus*	Dec-16	239	9.27	2579.8	278.2
Bon	*S. galilaeus*	Jan-17	200	6.43	2171.8	337.6
Bon	*S. galilaeus*	Feb-17	200	4.88	3642	746.5
Bon	*S. galilaeus*	Mar-17	200	5.58	7853.4	1406.9
Bon	*S. galilaeus*	Apr-17	200	7.5	6813.7	908.1
Bon	*S. galilaeus*	May-17	200	7.1	11778.5	1658.8
Bon	*S. galilaeus*	Jun-17	200	6.69	6290.3	939.9
Ton	*C. zillii*	Jul-16	204	4.93	909.7	184.4

Ton	*C. zillii*	Aug-16	220	5.3	100.3	18.9
Ton	*C. zillii*	Sep-16	239	10.88	453.9	41.7
Ton	*C. zillii*	Oct-16	241	7.77	656.7	84.6
Ton	*C. zillii*	Nov-16	240	6.01	983.6	163.8
Ton	*C. zillii*	Dec-16	294	9.67	180.6	18.7
Ton	*C. zillii*	Jan-17	146	2.87	716.1	249.6
Ton	*C. zillii*	Feb-17	200	4.38	2262.8	516.3
Ton	*C. zillii*	Mar-17	200	4.17	2570.8	616.3
Ton	*C. zillii*	Apr-17	200	6.93	1463.1	211.1
Ton	*C. zillii*	May-17	200	3.35	1523.7	454.4
Ton	*C. zillii*	Jun-17	200	2.9	540.2	186.6
Ton	*O. niloticus*	Jul-16	236	14.02	549.3	39.2
Ton	*O. niloticus*	Aug-16	239	15.85	2124.5	134
Ton	*O. niloticus*	Sep-16	241	15.96	1173.1	73.5
Ton	*O. niloticus*	Oct-16	240	16.86	7320.1	434.2
Ton	*O. niloticus*	Nov-16	242	16.4	7616.2	464.5
Ton	*O. niloticus*	Dec-16	240	15.61	5896.4	377.8
Ton	*O. niloticus*	Jan-17	200	14.45	1664.9	115.2
Ton	*O. niloticus*	Feb-17	200	10.85	3282.6	302.5
Ton	*O. niloticus*	Mar-17	200	13.05	2295.6	175.9
Ton	*O. niloticus*	Apr-17	200	21.74	3070.5	141.3
Ton	*O. niloticus*	May-17	200	13.29	10407.4	782.9
Ton	*O. niloticus*	Jun-17	200	15.92	6609	415.1
Ton	*S. galilaeus*	Jul-16	302	18.72	2530	135.1
Ton	*S. galilaeus*	Aug-16	238	15.68	3484.8	222.2
Ton	*S. galilaeus*	Sep-16	240	14.76	1431.5	97
Ton	*S. galilaeus*	Oct-16	239	15.6	11918.3	764
Ton	*S. galilaeus*	Nov-16	221	13.35	10943.7	819.8
Ton	*S. galilaeus*	Dec-16	260	15.56	6983.2	448.9
Ton	*S. galilaeus*	Jan-17	200	15.26	7678.8	503.2
Ton	*S. galilaeus*	Feb-17	200	13.86	10777.6	777.4
Ton	*S. galilaeus*	Mar-17	200	14.4	11170.3	775.8
Ton	*S. galilaeus*	Apr-17	200	13.35	11295.7	846.2
Ton	*S. galilaeus*	May-17	200	14.6	18440.3	1262.9
Ton	*S. galilaeus*	Jun-17	200	15.14	6402.7	423
Gol	*C. zillii*	Jul-16				
Gol	*C. zillii*	Aug-16				
Gol	*C. zillii*	Sep-16				
Gol	*C. zillii*	Oct-16				
Gol	*C. zillii*	Nov-16	27	0.43	15	34.9
Gol	*C. zillii*	Dec-16	21	0.34	1.4	4.2
Gol	*C. zillii*	Jan-17	27	0.99	9.4	9.5
Gol	*C. zillii*	Feb-17	13	0.58	14.3	24.6
Gol	*C. zillii*	Mar-17	20	0.75	15.6	20.7
Gol	*C. zillii*	Apr-17	40	0.68	26	38.5
Gol	*C. zillii*	May-17	80	2.08	15.1	7.3

Gol	*C. zillii*	Jun-17	33	0.52	9.2	17.7
Gol	*O. niloticus*	Jul-16				
Gol	*O. niloticus*	Aug-16				
Gol	*O. niloticus*	Sep-16				
Gol	*O. niloticus*	Oct-16				
Gol	*O. niloticus*	Nov-16	35	0.43	6.09	14.2
Gol	*O. niloticus*	Dec-16	42	1.02	8.7	8.5
Gol	*O. niloticus*	Jan-17	160	6.08	132.7	21.8
Gol	*O. niloticus*	Feb-17	200	7.53	346.4	46
Gol	*O. niloticus*	Mar-17	200	10.49	811.7	77.3
Gol	*O. niloticus*	Apr-17	200	11.6	1929.4	166.3
Gol	*O. niloticus*	May-17	200	15.26	610.3	40
Gol	*O. niloticus*	Jun-17	120	8.04	76.1	9.5
Gol	*S. galilaeus*	Jul-16				
Gol	*S. galilaeus*	Aug-16				
Gol	*S. galilaeus*	Sep-16				
Gol	*S. galilaeus*	Oct-16				
Gol	*S. galilaeus*	Nov-16	26	0.6	8.4	14
Gol	*S. galilaeus*	Dec-16	55	0.88	16.5	18.8
Gol	*S. galilaeus*	Jan-17	160	5.14	263.7	51.3
Gol	*S. galilaeus*	Feb-17	200	8.38	663.9	79.2
Gol	*S. galilaeus*	Mar-17	200	7.66	1003.7	131.1
Gol	*S. galilaeus*	Apr-17	200	8.92	833.3	93.4
Gol	*S. galilaeus*	May-17	103	5.92	65.1	11
Gol	*S. galilaeus*	Jun-17	27	0.67	18	26.7

Table S4.2. Gillnet selectivity of *Coptodon zillii*, *Oreochromis niloticus* and *Sarotherodon galilaeus* at Bontanga, Tono and Golinga reservoirs.

Table S4.2a. Summary of the proportion of fish captured by the different mesh sizes of gill nets and their mean total lengths. Ml: Mean length of fish, Prop.: Proportion of fish. A slash (/) indicates a mesh size not available at the reservoir.

Species	Net mesh size (mm)	Bontanga		Tono		Golinga	
		Ml (cm)	Prop. (%)	Ml (cm)	Prop. (%)	Ml (cm)	Prop. (%)
C. zillii	*16*	8.8±1.5	41.3	10.3±1.1	22.2	/	/
	22	9.4±1.8	38.1	10.8±1.4	13.9	12.3±1.6	33.3
	25	11.6±1.7	22.3	10±1.6	52.8	/	/
	32	/	/	/	/	13.4±1.8	15
	48	14.8±2.1	8.3	9.8±0.9	6.9	11.8±2.7	51.7
	51	/	/	10.5±2.2	2.8	/	/
	57	/	/	9.8±0.5	1.4	/	/
O. niloticus	*16*	11.1±1.4	1.7	/	/	/	/
	22	11.5±1.7	10.1			13±2.2	8.5
	25	10.9±1.7	8.9			12.4±0.7	2.1
	32	12.2±2.8	9.9	/	/	12.6±1.1	4.3
	48	12.8±1.2	29.9	14.1±1.3	6.5	12.9±1.4	21.3
	51	14.5±3.8	9.2	14.5±1.6	19.4	14.4±2.5	14.9
	57	12.4±1.4	30.4	14.9±1.8	45.4	14.8±2.2	48.9
	64	/	/	15.4±1.6	18.5	/	/
	70	/	/	17.8±1.7	10.2	/	/
S. galilaeus	*16*	8.9±1.5	16	/	/	/	/
	22	10.5±0.9	16.4	/	/	12.4±1	12.1
	25	11.3±1.6	14.5	/	/	12±0.6	1.5
	32	12.4±1.2	8	/	/	/	/
	48	12.8±1.8	23.1	/	/	12±1.2	28.7
	51	/	/	15.3±1.6	19.1	12.3±1.3	12.1
	57	13.3±2.1	22.1	15.6±1.9	41.8	13.6±2.6	45.7
	58	/	/	14.7±1.4	3.6	/	/
	64	/	/	15.5±1.6	16.4	/	/
	70	/	/	16.2±1.8	19.1	/	/

Table S4.2b. Individual data of *Coptodon zillii*, *Oreochromis niloticus* and *Sarotherodon galilaeus* collected from Bontanga, Tono and Golinga reservoirs.

Species, reservoir	*Coptodon zillii*, Bontanga					
Length (cm)	Mesh size (mm)				Total	% No
	16	*22*	*25*	*48*		
6	2				2	0.3
7	116	4	5		125	19.5
8	38	85	11		134	20.9
9	41	43	11		95	14.8
10	40	16	11		67	10.5
11	21	20	39	4	84	13.1
12	3	5	40	6	54	8.4
13	1	4	16	10	31	4.8
14	1		10	10	21	3.3
15	1			8	9	1.4
16				5	5	0.8
17				5	5	0.8
18		1		2	3	0.5
19		2		3	5	0.8
Total	264	180	143	53	640	100
% No	41.3	28.1	22.3	8.3	100	
# set	67	65	44	19	195	
No/set	3.9	2.8	3.3	2.8	3.3	
Length(cm)/NO	8.8	9.4	11.6	14.8	10.1	
SD Length(cm)/NO	1.5	1.8	1.7	2.1	2.4	

Species, reservoir	*Oreochromis niloticus*, Bontanga								
Length (cm)	Mesh size (mm)							Total	% No
	16	*22*	*25*	*32*	*48*	*51*	*57*		
7	1	4	1					6	0.8
8		6	13	1			1	21	2.9
9			4	10			2	16	2.2
10	4	1	6	19	10		20	60	8.3
11	4	25	25	7	36	10	51	158	21.9
12	3	25	9	12	70	17	81	217	30.1
13		12	3	6	61	10	34	126	17.5
14			2	6	30	8	17	63	8.8
15			1	3	8	5	4	21	2.9
16				1		9	7	17	2.4
17				1			1	2	0.3
18							1	1	0.1
19				4		1		5	0.7
20				1		4		5	0.7
21						1		1	0.1
22									
23									
24									
25									
26									
27									
28									
29									
30									
31									
32									
33									
34									
35									
36									
37						1		1	0.1
Total	12	73	64	71	215	66	219	720	100
% No	1.7	10.1	8.9	9.9	29.9	9.2	30.4	100	
# set	153	232	307	137	237	17	118	1201	
No/set	0.1	0.3	0.2	0.5	0.9	3.9	1.9	0.6	
Length(cm)/NO	11.1	11.5	10.9	12.2	12.8	14.5	12.4	12.5	
SD Length(cm)/NO	1.4	1.7	1.7	2.8	1.2	3.8	1.4	2.1	

Species, reservoir	*Sarotherodon galilaeus*, Bontanga							
Length (cm)	Mesh size (mm)						Total	% No
	16	*22*	*25*	*32*	*48*	*57*		
6	21				2	1	24	1.5
7	59				4		63	3.9
8	85	4	50	2	7		148	9.1
9	16	46		3	13	4	82	5
10	56	133	7	5	14	13	228	14
11	15	68	89	17	77	76	342	21
12	4	12	85	72	99	99	371	22.8
13	1	4	5	21	35	86	152	9.3
14	2			10	96	10	118	7.2
15					24	21	45	2.8
16					4	21	25	1.5
17					2	14	16	1
18						11	11	0.7
19								
20						2	2	0.1
21						2	2	0.1
Total	259	267	236	130	377	360	1629	100
% No	16	16.4	14.5	8	23.1	22.1	100	
# set	153	232	307	137	237	118	1201	
No/set	1.7	1.2	0.8	0.9	1.6	3.1	1.4	
Length(cm)/NO	8.9	10.5	11.3	12.4	12.8	13.3	11.6	
SD Length(cm)/NO	1.5	0.9	1.6	1.2	1.8	2.1	2.3	

Species, reservoir	*Coptodon zillii*, Tono							
Length (cm)	Mesh size (mm)						Total	% No
	16	*22*	*25*	*48*	*51*	*57*		
7			38				38	5.3
8	5	1	34		1		41	5.7
9	67	32	121	33	11	8	272	37.8
10	40	23	89	15	5	1	173	24
11	29	25	53	1		1	109	15.1
12	18	12	24				54	7.5
13	1	5	9				15	2.1
14			7		1		8	1.1
15		1	3	1	1		6	0.8
16		1	1		1		3	0.4
17			1				1	0.1
Total	160	100	380	50	20	10	720	100
% No	22.2	13.9	52.8	6.9	2.8	1.4	100	
# set	4	3	11	6	26	36	134	
No/set	40	33.3	34.5	8.3	0.8	0.3	5.4	
Length(cm)/NO	10.3	10.8	10	9.8	10.5	9.8	10.2	
SD Length(cm)/NO	1.1	1.4	1.6	0.9	2.2	0.5	1.5	

Species, reservoir	*Oreochromis niloticus*, Tono						
Length (cm)	Mesh size (mm)					Total	% No
	48	*51*	*57*	*64*	*70*		
10			2			2	0.2
11	1	5	3			9	0.8
12	13	28	40	6		87	8.1
13	24	44	101	31	1	201	18.6
14	13	54	133	58	7	265	24.5
15	13	42	97	39	5	196	18.1
16	4	20	59	26	11	120	11.1
17	2	13	33	24	37	109	10.1
18		1	10	11	27	49	4.5
19		1	7	4	15	27	2.5
20		2	1	1	4	8	0.7
21							
22			1		1	2	0.2
23			3		1	4	0.4
24					1	1	0.1
Total	70	210	490	200	110	1080	100
% No	6.5	19.4	45.4	18.5	10.2	100	
# set	6	26	36	18	29	134	
No/set	11.7	8.1	13.6	11.1	3.8	8.1	
Length(cm)/NO	14.1	14.5	14.9	15.4	17.8	15.1	
SD Length(cm)/NO	1.3	1.6	1.8	1.6	1.7	1.9	

Species, reservoir	*Sarotherodon galilaeus*, Tono						
Length (cm)	Mesh size (mm)					Total	% No
	51	*57*	*58*	*64*	*70*		
10	1	3	1		1	6	0.5
11	1	4		3	1	9	0.8
12	10	22	1	3	1	37	3.4
13	26	53	4	16	11	110	10
14	52	103	24	41	44	264	24
15	48	101	5	46	34	234	21.3
16	36	75	3	39	47	200	18.2
17	19	46	1	17	28	111	10.1
18	14	27		13	30	84	7.6
19	1	15		1	11	28	2.5
20	2	10	1	1	2	16	1.5
21		1				1	0.1
Total	210	460	40	180	210	1100	100
% No	19.1	41.8	3.6	16.4	19.1	100	
# set	26	36	1	18	29	134	
No/set	8.1	12.8	40	10	7.2	8.2	
Length(cm)/NO	15.3	15.6	14.7	15.5	16.2	15.6	
SD Length(cm)/NO	1.6	1.9	1.4	1.6	1.8	1.8	

Species, reservoir	*Coptodon zillii*, Golinga							
Length (cm)	Mesh size (mm)						Total	% No
	22	*25*	*32*	*48*	*51*	*57*		
8	1			4			5	8.3
9	1			6			7	11.7
10	1			2			3	5
11	3		2	4			9	15
12	5		3	6			14	23.3
13	6		1	1			8	13.3
14	2		1	4			7	11.7
15	1		1	2			4	6.7
16			1				1	1.7
17				2			2	3.3
Total	20		9	31			60	100
% No	33.3		15	51.7			100	
# set	5	3	2	17	7	21	55	
No/set	4		4.5	1.8			1.1	
Length(cm)/NO	12.3		13.4	11.8			12.2	
SD Length(cm)/NO	1.6		1.8	2.7			2.3	

Species, reservoir	*Oreochromis niloticus*, Golinga							
Length (cm)	Mesh size (mm)						Total	% No
	22	*25*	*32*	*48*	*51*	*57*		
7						2	2	0.2
8						3	3	0.3
9				1		1	2	0.2
10	2		2	5	5	2	16	1.7
11	20	5	6	41	15	19	106	11.3
12	24	10	19	77	23	59	212	22.6
13	20	5	9	40	21	77	172	18.3
14	8		3	19	32	82	144	15.3
15	1			11	13	87	112	11.9
16	1		1	4	14	71	91	9.7
17	1			1	6	32	40	4.3
18	1			1	4	9	15	1.6
19					1	5	6	0.6
20					4	2	6	0.6
21	1				1	4	6	0.6
22						4	4	0.4
23								
24						1	1	0.1
25								
26	1				1		2	0.2
Total	80	20	40	200	140	460	940	100
% No	8.5	2.1	4.3	21.3	14.9	48.9	100	
# set	5	3	2	17	7	21	55	
No/set	16	6.7	20	11.8	20	21.9	17.1	
Length(cm)/NO	13	12.4	12.6	12.9	14.4	14.8	14	
SD Length(cm)/NO	2.2	0.7	1.1	1.4	2.5	2.2	2.2	

Species, reservoir	*Sarotherodon galilaeus*, Golinga						
Length (cm)	Mesh size (mm)					Total	% No
	22	*25*	*48*	*51*	*57*		
5					1	1	0.2
6					12	12	1.8
7					6	6	0.9
8			1		2	3	0.5
9			4		1	5	0.8
10	10	1	21	9	7	48	7.2
11	10	3	68	25	12	118	17.8
12	37	6	65	22	53	183	27.6
13	17		21	13	76	127	19.2
14	6		7	8	59	80	12.1
15			1	3	35	39	5.9
16			2		13	15	2.3
17					14	14	2.1
18					4	4	0.6
19					5	5	0.8
20					1	1	0.2
21					2	2	0.3
Total	80	10	190	80	303	663	100
% No	12.1	1.5	28.7	12.1	45.7	100	
# set	5	3	17	7	21	55	
No/set	16	3.3	11.2	11.4	14.4	12.1	
Length(cm)/NO	12.4	12	12	12.3	13.6	12.8	
SD Length(cm)/NO	1	0.6	1.2	1.3	2.6	2.1	

Table S4.3. Correction factor for gillnet selection of *Coptodon zillii, Oreochromis niloticus* and *Sarotherodon galilaeus* catches at Bontanga (Bon), Tono (Ton) and Golinga (Gol) reservoirs. The selectivity corrected catch (final lfq catch) is observed lfq*i*/selectivity probability, where *i* is length class *i*. Correction factor of 1 means the number of the individuals observed for the length remains unchanged and correction factor of 0.5 means doubling the number of individuals measured at that length.

	C.zillii			*O. niloticus*			*S. galilaeus*		
Total length (cm)	Bon	Ton	Gol	Bon	Ton	Gol	Bon	Ton	Gol
1	0.14	0.26	0.17	0.59	0.00	0.19	0.29	0.00	0.38
2	0.24	0.28	0.19	0.74	0.00	0.24	0.41	0.00	0.44
3	0.37	0.31	0.20	0.86	0.00	0.30	0.55	0.01	0.51
4	0.53	0.34	0.23	0.95	0.00	0.37	0.69	0.02	0.58
5	0.71	0.37	0.25	1.00	0.00	0.44	0.81	0.03	0.65
6	0.86	0.40	0.27	1.00	0.00	0.53	0.91	0.06	0.72
7	0.96	0.44	0.30	0.94	0.01	0.61	0.98	0.10	0.79
8	1.00	0.47	0.32	0.85	0.03	0.70	1.00	0.16	0.85
9	0.96	0.51	0.35	0.74	0.07	0.78	0.99	0.24	0.90
10	0.85	0.54	0.38	0.61	0.15	0.86	0.97	0.35	0.94
11	0.70	0.58	0.42	0.48	0.29	0.93	0.94	0.47	0.98
12	0.54	0.62	0.45	0.36	0.46	0.97	0.92	0.61	0.99
13	0.39	0.66	0.48	0.26	0.67	1.00	0.91	0.75	1.00
14	0.28	0.70	0.52	0.17	0.85	1.00	0.90	0.87	0.99
15	0.21	0.74	0.56	0.11	0.96	0.98	0.89	0.96	0.97
16	0.17	0.78	0.60	0.07	1.00	0.93	0.87	1.00	0.93
17	0.15	0.82	0.64	0.04	0.95	0.87	0.81	0.99	0.88
18	0.13	0.86	0.68	0.02	0.84	0.78	0.73	0.94	0.83
19	0.12	0.91	0.73	0.01	0.68	0.69	0.62	0.85	0.76
20	0.10	0.95	0.77	0.01	0.51	0.59	0.50	0.72	0.69
21	0.07	1.00	0.82	0.00	0.33	0.49	0.38	0.59	0.62
22	0.05		0.86	0.00	0.19	0.40	0.27	0.45	0.54
23	0.03		0.91	0.00	0.10	0.32	0.18	0.33	0.47
24	0.02		0.95	0.00	0.04	0.24		0.23	
25	0.01		1.00	0.00	0.02	0.18			
26	0.01			0.00	0.01	0.13			
27				0.00		0.09			
28				0.00		0.06			
29-39				0.00					

Table S4.4. Parameter estimates (maximum density-max.) of soVBGF based on MA of 3 and 7 of the target fish species from reservoirs assessed with the bootstrapped ELEFAN with GA of TropFishR. Estimates based on the pooled length-frequency data of Tono, Bontanga and Golinga reservoirs collected from July 2016 to June 2017. Lower and upper denote 95% confidence interval of the estimates.

Species	Parameter	MA=3			MA=7		
		Mod	Lower	Upper	Mod	Lower	Upper
C. zillii	*L*∞ (cm)	20.56	18.19	22.41	20.56	15.55	22.27
	K (/yr)	0.73	0.30	1.08	0.69	0.51	1.55
	t_{anchor}	0.27	0.19	0.83	0.36	0.18	0.89
	C	0.68	0.21	0.94	0.81	0.35	0.97
	ts	0.36	0.16	0.83	0.65	0.35	0.78
	Φ	2.49	1.99	2.73	2.47	2.09	2.89
O. niloticus	*L*∞ (cm)	26.03	24.26	28.08	26.06	19.51	28.15
	K (/yr)	0.26	0.22	0.69	0.83	0.44	1.53
	t_{anchor}	0.60	0.16	0.84	0.45	0.18	0.78
	C	0.60	0.15	0.89	0.50	0.22	0.95
	ts	0.53	0.18	0.86	0.81	0.12	0.93
	Φ	2.24	2.11	2.73	2.75	2.23	3.08
S. galilaeus	*L*∞ (cm)	22.91	17.24	24.29	17.60	17.15	18.00
	K (/yr)	0.32	0.30	1.31	0.82	0.63	1.10
	t_{anchor}	0.57	0.14	0.87	0.63	0.21	0.80
	C	0.70	0.17	0.90	0.68	0.33	0.90
	ts	0.41	0.11	0.89	0.39	0.23	0.63
	Φ	2.23	1.95	2.89	2.41	2.27	2.55

Table S4.5a. Estimated mortality values (Z , M and F), exploitation rate (E) and biological reference points of fishing mortality (Fmax, F0.1, F0.5) for the target species of Tono, Bontanga and Golinga reservoirs based on the pooled VBGF parameters with MA setting of 3. Max: maximum density value and lower and upper: the confidence intervals of the bootstrapping approach. The M estimate of a species is a common value for all reservoirs.

Species	Parameter (/yr)	**Bontanga**			**Tono**			**Golinga**		
		Mod	Lower	Upper	Mod	Lower	Upper	Mod	Lower	Upper
C. zillii	*Z*	1.07	0.97	3.00	1.82	1.61	5.26	1.31	1.18	3.38
	M	0.73	0.61	1.65	0.73	0.61	1.65	0.73	0.61	1.65
	F	0.34	0.27	1.46	1.08	0.82	4.09	0.56	0.47	1.97
	E	0.32	0.28	0.49	0.59	0.51	0.78	0.43	0.40	0.58
	F0.1	0.81	0.66	1.81	0.65	0.54	1.88	0.76	0.62	4.49
	Fmax	6.99	1.69	7.00	4.99	1.52	6.74	7.00	1.83	7.00
	F0.5	0.52	0.44	1.26	0.48	0.41	1.38	0.53	0.41	1.45
O. niloticus	*Z*	1.11	1.01	2.76	1.42	1.25	3.42	1.05	0.88	2.68
	M	0.52	0.45	1.08	0.52	0.45	1.08	0.52	0.45	1.08
	F	0.60	0.49	1.72	0.94	0.71	2.23	0.55	0.35	1.79
	E	0.54	0.49	0.62	0.66	0.57	0.65	0.52	0.40	0.67
	F0.1	1.01	0.82	1.98	0.89	0.60	1.47	0.80	0.67	1.69
	Fmax	6.98	2.38	7.00	7.00	2.71	7.00	7.00	1.99	7.00
	F0.5	0.58	0.50	1.22	0.77	0.48	1.29	0.52	0.45	1.18
S. galilaeus	*Z*	2.55	1.77	6.46	2.80	2.13	3.00	2.13	1.84	3.96
	M	0.81	0.59	1.85	0.81	0.59	1.85	0.81	0.59	1.85
	F	1.59	0.86	5.09	1.21	0.65	1.26	1.30	0.90	2.74
	E	0.62	0.49	0.79	0.43	0.31	0.42	0.61	0.49	0.69
	F0.1	0.96	0.62	2.38	2.67	2.02	2.93	0.85	0.68	4.31
	Fmax	2.03	1.43	7.00	6.92	6.45	7.00	7.01	3.48	7.00
	F0.5	0.64	0.44	1.78	2.91	1.76	3.10	0.65	0.53	2.33

Table 4.5b. Estimated mortality values (Z , M and F), exploitation rate (E) and biological reference points of fishing mortality (Fmax, F0.1, F0.5) for the target species of Tono, Bontanga and Golinga reservoirs based on the pooled VBGF parameters with MA setting of 7. Max: maximum density value and lower and upper: the confidence intervals of the bootstrapping approach. The M estimate of a species is a common value for all reservoirs.

Species	Parameter (/yr)	**Bontanga**			**Tono**			**Golinga**		
		Mod	Lower	Upper	Mod	Lower	Upper	Mod	Lower	Upper
C. zillii	*Z*	2.01	1.42	4.77	3.25	1.73	15.36	2.08	1.55	6.27
	M	1.68	0.92	2.24	1.68	0.92	2.24	1.68	0.92	2.24
	F	0.82	0.17	2.88	1.76	0.54	13.49	0.95	0.23	4.38
	E	0.41	0.12	0.60	0.54	0.31	0.88	0.46	0.15	0.70
	F0.1	1.37	0.92	2.39	1.24	0.95	2.56	1.51	0.90	2.85
	Fmax	2.33	1.70	7.00	2.55	1.91	7.00	2.59	1.74	7.00
	F0.5	0.88	0.65	2.00	0.91	0.69	2.23	0.90	0.65	1.94
O. niloticus	*Z*	3.27	1.65	4.90	3.69	1.53	4.85	3.15	1.85	5.03
	M	1.25	0.81	2.08	1.25	0.81	2.08	1.25	0.81	2.08
	F	1.98	0.64	3.34	2.47	0.36	3.40	1.84	0.88	3.22
	E	0.61	0.39	0.68	0.67	0.24	0.70	0.58	0.48	0.64
	F0.1	2.35	1.39	3.33	1.71	1.00	3.19	2.00	1.17	2.96
	Fmax	4.15	2.84	7.00	3.81	2.88	7.00	3.80	2.54	7.00
	F0.5	1.47	0.93	2.36	1.10	0.74	3.35	1.19	0.78	2.83
S. galilaeus	*Z*	2.71	1.87	3.41				2.89	2.87	2.91
	M	1.32	1.13	1.72	1.32	1.13	1.72	1.32	1.13	1.72
	F	1.32	0.48	1.75				1.21	1.17	1.25
	E	0.49	0.26	0.51				0.42	0.41	0.43
	F0.1	2.25	1.41	4.05				2.25	2.18	2.31
	Fmax	5.31	4.91	7.00				NaN	7.00	7.00
	F0.5	1.31	1.24	2.14				2.35	2.33	2.37

ANNEX III

Supplements for Chapter 5

Table S5.1. Parameter estimates based on MA of 5 and 9 of for *Auchenoglanis occidentalis* from Bontanga reservoir collected from July 2016 to June 2017. Lower and upper denote 95% confidence interval of the estimates.

Parameter	MA=5			MA=9		
	Max.	Lower	Upper	Max	Lower	Upper
Linf	33.15	27.19	35.31	30.98	28.19	35.65
K	0.22	0.17	0.36	0.94	0.19	1.18
t_anchor	0.55	0.17	0.80	0.31	0.16	0.87
C	0.52	0.27	0.92	0.70	0.19	0.93
ts	0.58	0.27	0.69	0.55	0.11	0.79
phiL	2.39	2.09	2.65	2.95	2.18	3.17
M_Then	0.47	0.35	0.65	0.45	0.38	1.52
Z	0.92	0.56	1.20	0.89	0.63	4.10
FM	0.50	0.16	0.62	0.46	0.21	2.59
L50	14.16	12.82	15.67	14.41	12.42	16.00
L75	15.32	13.99	16.78	15.28	13.27	17.31
t50	2.4			0.6		
t75	2.7			0.65		
N	375573	330380	1275288	59874	43604	731488
B	13.18	10.65	47.25	2.06	1.43	29.68
F01	0.97	0.82	1.95	1.04	0.87	3.03
Fmax	1.72	1.44	4.30	1.87	1.53	5.45
F05	0.54	0.45	1.37	0.59	0.48	1.84
FF01	0.33	0.15	0.55	0.45	0.20	1.00
FFmax	0.16	0.06	0.29	0.44	0.11	0.55
FF05	0.50	0.21	0.91	1.34	0.36	1.60
E	0.54	0.29	0.52	0.52	0.33	0.63

Table S5.2. Parameter estimates based on MA of 5 and 9 of for *Auchenoglanis occidentalis* from **Tono reservoir** collected from July 2016 to June 2017. Lower and upper denote 95% confidence interval of the estimates.

Parameter	MA=5			MA=9		
	Max.	Lower	Upper	Max	Lower	Upper
Linf	38.71	37.47	42.59	38.01	36.05	40.46
K	0.31	0.16	0.37	0.35	0.28	0.98
t_anchor	0.40	0.24	0.77	0.59	0.22	0.79
C	0.45	0.09	0.83	0.43	0.23	0.86
ts	0.49	0.13	0.83	0.71	0.34	0.94
phiL	2.67	2.36	2.82	2.70	2.57	3.20
M_Then	0.52	0.32	0.60	0.57	0.48	1.23
Z	0.71	0.45	0.83	0.71	0.65	2.29
FM	0.17	0.07	0.34	0.15	0.07	1.01
L50	29.31	27.66	30.49	29.39	27.74	30.74
L75	30.61	28.97	31.80	30.64	29.00	31.97
t50	5.1			3.85		
t75	5.7			4.23		
N	279259	449793	2229240	621709	92973	2497564
B	139.94	51.88	259.79	79.26	12.31	316.09
F01	0.90	0.60	1.35	0.98	0.83	2.49
Fmax	3.53	2.17	5.68	3.56	3.23	7.00
F05	0.77	0.51	1.14	0.80	0.72	2.12
FF01	0.21	0.07	0.51	0.09	0.04	0.60
FFmax	0.05	0.02	0.15	0.02	0.01	0.20
FF05	0.24	0.08	0.63	0.09	0.05	0.77
E	0.24	0.16	0.41	0.21	0.11	0.44

Figure S5.1. Length frequency histograms with the growth curves obtained through the bootstrapped ELEFAN with GA analysis superimposed for *A. occidentalis* collected from July 2016 to June 2017 at (a) Lake Bontanga and (b) Lake Tono.

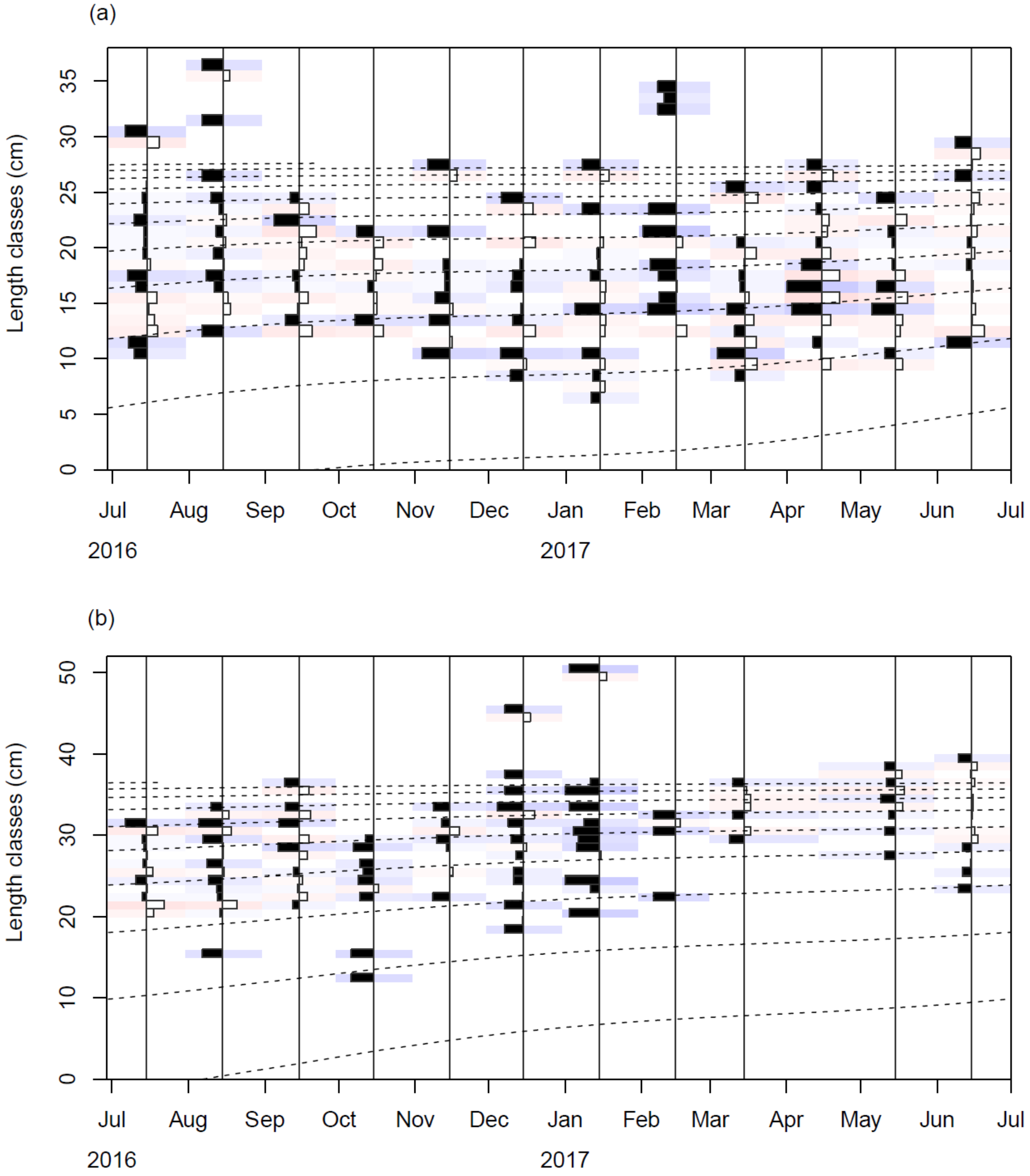
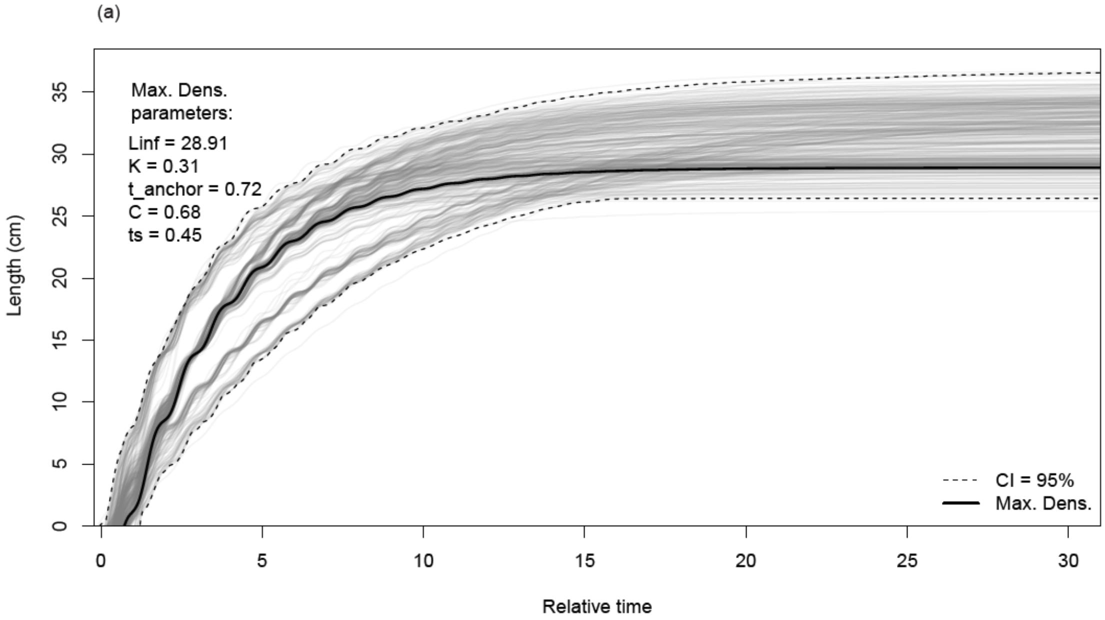


Figure S5.2. von Bertalanffy growth curves for *A. occidentalis* collected from (a) Lake Bontanga and (b) Lake Tono. Linf = the asymptotic length of the fish, K = growth coefficient, t_anchor = indicates the fraction of the year where yearly repeating growth curves cross length equal to zero, C = is a constant indicating the amplitude of the oscillation, ts = is the fraction of a year (relative to the age of recruitment, t = 0) where the sine wave oscillation begins (i.e., turns positive).



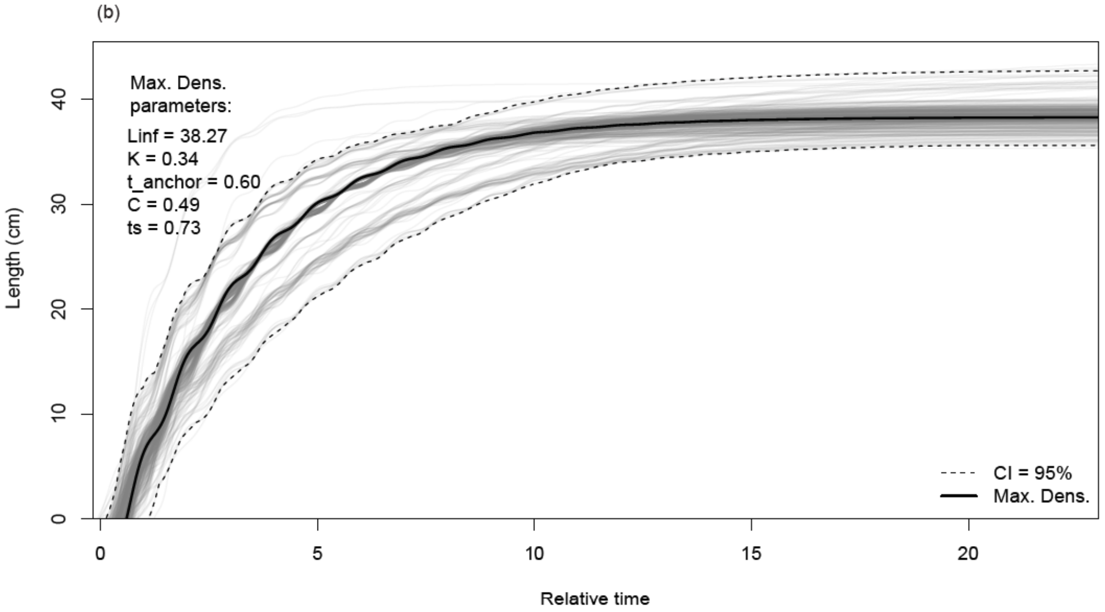
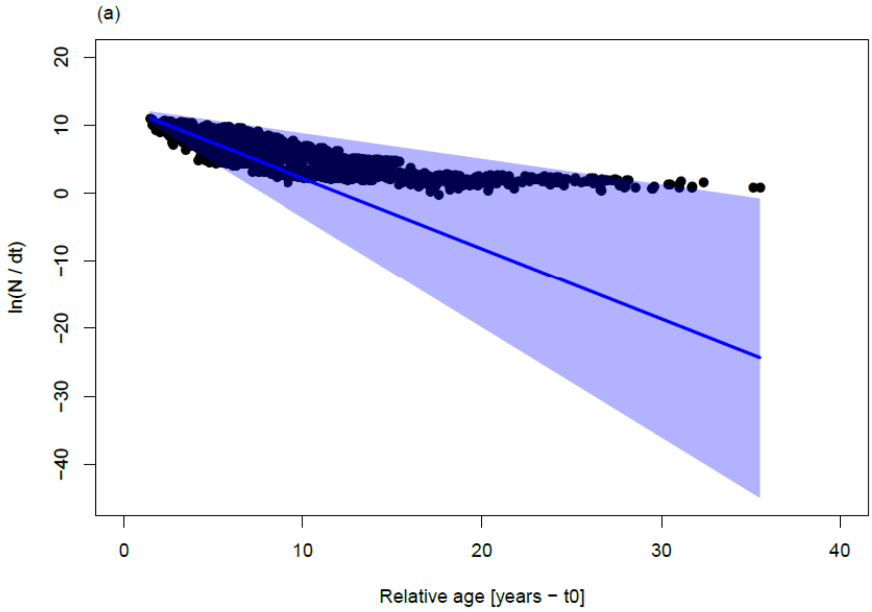


Figure S5.3. Bootstrapped linearised length-converted catch curve based on one year (July 2016 to June 2017) catch for *A. occidentalis* collected from (a) Lake Bontanga and (b) Lake Tono.



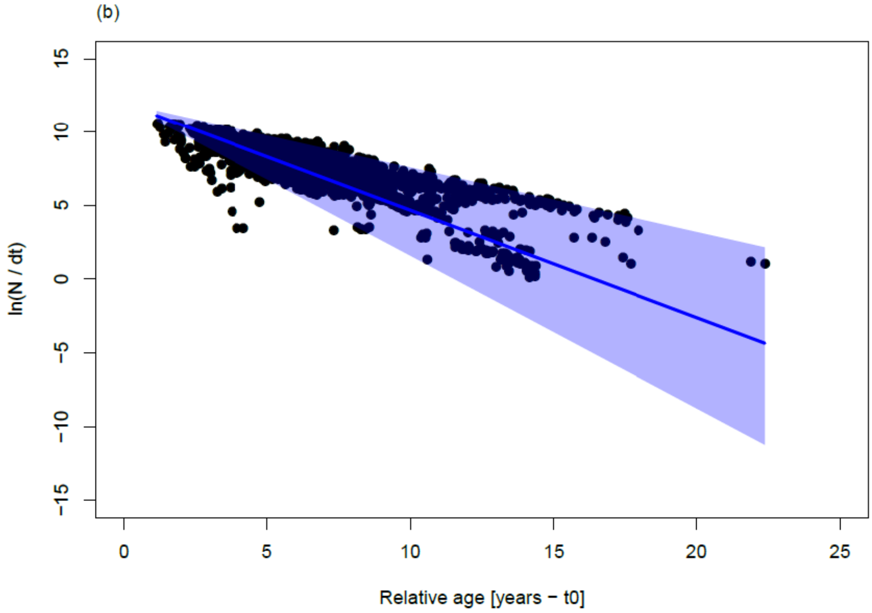
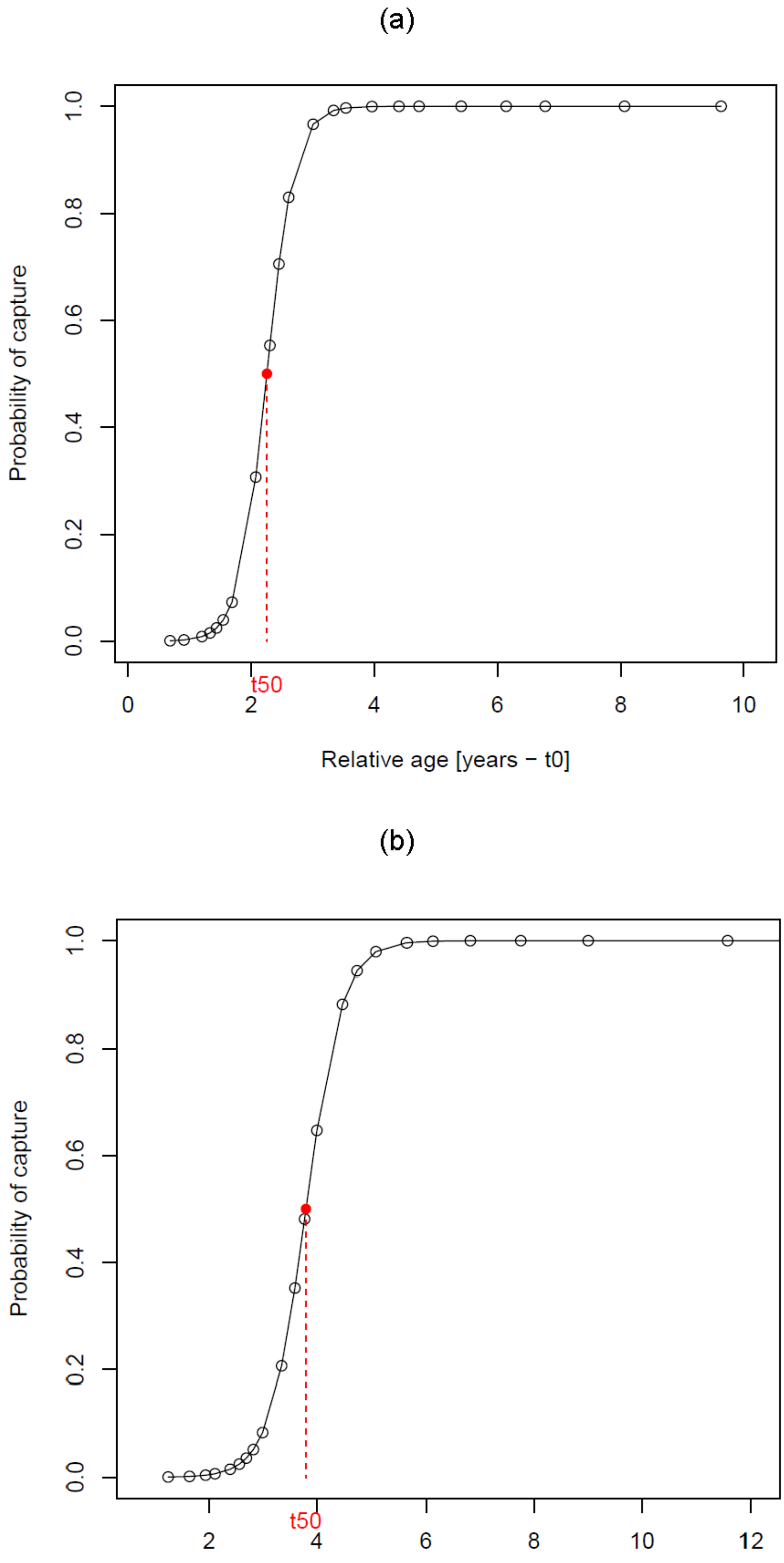


Figure S5.4. Probability of capture of *A. occidentalis* from (a) Lake Bontanga and (b) Lake Tono estimated from ascending axis of the linearised length-converted catch curve. t50 is the time corresponding to the length at first capture (*Lc*).



ANNEX IV

Supplements for Chapter 6

Table S6.1. Input parameters used to calculate consumption per unit of biomass (Q/B) values and production per unit of biomass (P/B) for fish groups obtained from Abobi et al. (2019a) and Abobi et al. (2019b). *a* = constant of length-weight relationship, *b* = allometric coefficient of length-weight relationship, *L*∞ = asymptotic length, *W*∞ = asymptotic body weight, T(°C) = water temperature, Ar = is the aspect ratio of the caudal fin which is defined as Ar=h2/s, where h is the height of the caudal fin (mm) and s is the surface area (mm^2) extending to the narrowest part of the caudal peduncle, H and D = are binary variables that define whether the predator is herbivorous (h=1, d=0), detritivore (h=0, d=1) or carnivore (h=0, d=0). * Values obtained from Fishbase (Froese and Pauly, 2019).

Species	Reservoir	*a*	*b*	*L*∞	*W*∞	T(°C)	Ar*	H*	D*
A. occidentalis	Tono	0.01	3.10	38.3	589.1	27.7	1.52	0	0
	Bontanga	0.01	2.93	28.91	229.1	28.6	1.52	0	0
C. zillii	Tono	0.02	3.04	20.6	152.9	27.7	1.57	1	0
	Bontanga	0.2	2.89	20.6	147.9	28.6	1.57	1	0
	Golinga	0.1	3.1	20.6	166.8	28.1	1.57	1	0
O. niloticus	Tono	0.02	2.88	25.9	292.2	27.7	1.57	1	0
	Bontanga	0.02	2.93	25.9	313.4	28.6	1.57	1	0
	Golinga	0.02	2.95	25.9	324.1	28.1	1.57	1	0
S. galilaeus	Tono	0.03	2.84	17.8	97.7	27.7	1.57	1	0
	Bontanga	0.02	2.97	17.8	108.5	28.6	1.57	1	0
	Golinga	0.02	3.00	17.8	109.2	28.1	1.57	1	0

Table S6.2. Diet matrix (as Ecopath input) of the largest reservoir's (Tono) food web model, detailing the proportional flows from all prey items (rows) to predators (columns).

	Prey \ Predator	1	2	3	4	5	6	7	8	9	10	11	12	13	14
1	Predatory birds	0	0	0	0	0	0	0	0	0	0	0	0	0	0
2	Crocodiles	0	0	0	0	0	0	0	0	0	0	0	0	0	0
3	*C. gariepinus*	0.05	0.08	0.025	0.005	0	0	0	0	0	0	0	0	0	0
4	*H. fasciatus*	0.03	0.1	0.005	0.02	0	0	0	0	0	0	0	0	0	0
5	*Mormyrus spp.*	0	0.005	0.001	0.005	0	0	0	0	0	0	0	0	0	0
6	*A. occidentalis*	0.09	0.23	0.0625	0.02	0	0	0.002	0	0	0	0	0	0	0
7	*Synodontis/Schilbe spp.*	0.12	0.1	0.05	0.02	0	0	0	0	0	0	0	0	0	0
8	*P. leonensis*	0.05	0.11	0.002	0.05	0	0.005	0.001	0	0	0	0	0	0	0
9	*O. niloticus*	0.18	0.05	0.03	0.115	0	0.018	0.14	0.2	0	0	0	0	0	0
10	*S. galilaeus*	0.35	0.22	0.18	0.335	0	0.0265	0.184	0.2	0	0	0	0	0	0
11	*C. zillii*	0.05	0.065	0.01	0.12	0	0.0265	0.095	0	0	0	0	0	0	0
12	Zooplankton	0	0	0.05	0.1	0.1	0.032	0.05	0.23	0.03	0.05	0.1	0.05	0.06	0.01
13	Insects and larvae	0	0	0.1	0.115	0.35	0.517	0.105	0.12	0.02	0	0.05	0	0.02	0
14	Zoobenthos	0	0.04	0.385	0.095	0.4	0	0.103	0.1	0.02	0.05	0	0	0	0.02
15	Phytoplankton	0	0	0.05	0	0.05	0.106	0	0.15	0.83	0.85	0.28	0.85	0.35	0.37
16	Macrophytes	0	0	0	0	0	0.094	0.22	0	0	0	0.5	0	0	0
17	Detritus	0	0	0.05	0	0.1	0.175	0.1	0	0.1	0.05	0.07	0.1	0.57	0.6
	Import	0.08	0	0	0	0	0	0	0	0	0	0	0	0	0
	Sum	1	1	1.0005	1	1	1	1	1	1	1	1	1	1	1

Table S6.3. Diet matrix (as Ecopath input) of the intermediate-sized reservoir's (Bontanga) food web model, detailing the proportional flows from all prey items (rows) to predators (columns).

	Prey \ Predator	1	2	3	4	5	6	7	8	9	10	11	12	13	14
1	Predatory birds	0	0	0	0	0	0	0	0	0	0	0	0	0	0
2	*C. gariepinus*	0.1	0.025	0.005	0	0	0	0	0	0	0	0	0	0	0
3	*H. fasciatus*	0.03	0.005	0.02	0	0	0	0	0	0	0	0	0	0	0
4	*Mormyrus spp.*	0	0.02	0.02	0	0	0	0	0	0	0	0	0	0	0
5	*A. occidentalis*	0.1	0.01	0.02	0	0	0	0	0	0	0	0	0	0	0
6	*B. nurse*	0.1	0.035	0.155	0	0.016	0	0	0	0	0	0	0	0	0
7	*Heterotis niloticus*	0	0.05	0	0	0	0	0	0	0	0	0	0	0	0
8	*P. leonensis*	0.05	0	0.05	0	0.025	0	0.1	0	0	0	0	0	0	0
9	*O. niloticus*	0.185	0.03	0.015	0	0.01	0.05	0	0.2	0	0	0	0	0	0
10	*S. galilaeus*	0.3	0.165	0.215	0	0.02	0.04	0	0.2	0	0	0	0	0	0
11	*C. zillii*	0.025	0.01	0.02	0	0.02	0.02	0	0	0	0	0	0	0	0
12	Zooplankton	0	0.05	0.1	0.1	0.024	0.02	0.12	0.23	0.03	0.05	0.1	0.05	0.06	0.01
13	Insects and larvae	0	0.1	0.28	0.35	0.471	0.35	0.3	0.12	0.02	0	0.05	0	0.02	0
14	Zoobenthos	0	0.4	0.1	0.4	0	0.03	0.2	0.1	0.02	0.05	0	0	0	0.02
15	Phytoplankton	0	0.05	0	0.05	0.142	0.07	0.05	0.15	0.83	0.85	0.28	0.85	0.35	0.37
16	Macrophytes	0	0	0	0	0.087	0.4	0.15	0	0	0	0.5	0	0	0
17	Detritus	0	0.05	0	0.1	0.185	0.02	0.08	0	0.1	0.05	0.07	0.1	0.57	0.6
	Import	0.11	0	0	0	0	0	0	0	0	0	0	0	0	0
	Sum	1	1	1	1	1	1	1	1	1	1	1	1	1	1

Table S6.4. Diet matrix (as Ecopath input) of the smallest reservoir's (Golinga) food web model, detailing the proportional flows from all prey items (rows) to predators (columns).

	Prey \ Predator	1	2	3	4	5	6	7	8	9	10	11	12	13	14
1	*Clarias gariepinus*	0.025	0.005	0	0	0	0	0	0	0	0	0	0	0	0
2	*H. fasciatus*	0.005	0.02	0	0	0	0	0	0	0	0	0	0	0	0
3	*Mormyrus spp.*	0.02	0.02	0	0	0	0.02	0	0	0	0	0	0	0	0
4	*Heterotis niloticus*	0.05	0	0	0	0	0.02	0	0	0	0	0	0	0	0
5	*P. leonensis*	0	0.05	0	0.1	0	0.001	0	0	0	0	0	0	0	0
6	*Synodontis/Schilbe spp.*	0.03	0.01	0	0	0	0	0	0	0	0	0	0	0	0
7	*B. nurse*	0.03	0.055	0	0	0	0.1	0	0	0	0	0	0	0	0
8	*Labeo spp.*	0.001	0.03	0	0	0	0.01	0	0	0	0	0	0	0	0
9	*O. niloticus*	0.039	0.115	0	0	0.2	0.1	0.08	0	0	0	0	0	0	0
10	*S. galilaeus*	0.23	0.175	0	0	0.2	0.15	0.065	0	0	0	0	0	0	0
11	*C. zillii*	0.02	0.02	0	0	0	0.02	0	0	0	0	0	0	0	0
12	Zooplankton	0.05	0.1	0.1	0.12	0.23	0.05	0.02	0.03	0.03	0.05	0.1	0.01	0.03	0.01
13	Insects and larvae	0.05	0.3	0.35	0.3	0.12	0.105	0.315	0.05	0.02	0	0.05	0	0.02	0
14	Zoobenthos	0.35	0.1	0.4	0.2	0.1	0.103	0.03	0.03	0.02	0.05	0	0	0.03	0.02
15	Phytoplankton	0.05	0	0.05	0.05	0.15	0	0.07	0.25	0.83	0.85	0.28	0.85	0.35	0.37
16	Macrophytes	0	0	0	0.15	0	0.221	0.4	0.01	0	0	0.5	0	0	0
17	Detritus	0.05	0	0.1	0.08	0	0.1	0.02	0.63	0.1	0.05	0.07	0.14	0.57	0.6
	Import	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Sum	1	1	1	1	1	1	1	1	1	1	1	1	1	1

Table S6.5. Comparison of system statistics and ecological indicators for the three studied reservoirs (Tono, Bontanga and Golinga) in comparison to the range of similar lake EwE models presented in literature. A "-" sign represents that the respective value was not calculated. For a visual overview see Fig. 6.4.

Parameter	Tono	Bontanga	Golinga	Ayamé[a]	Bagré[b]	Koka[c]	Ubolratana[d]	Parakrama Samudra[d]	Wyra[e]
Sum of all consumption (t km^{-2} yr^{-1})	3192.4	4551.8	4187.1	3593.1	1232.1	2162.9	2641.6	9909.6	-
Sum of all exports (t km^{-2} yr^{-1})	5746.7	3331.7	4461.0	-	354.7	2790.9	3211.3	2482.2	3171.2
Sum of all respiratory flows (t km^{-2} yr^{-1})	2046.0	2874.0	2726.0	-	787.5	1256.1	1512.8	7188.1	-
Sum of all flows into detritus (t km^{-2} yr^{-1})	6855.5	5133.6	5956.1	1210.6	652.0	3175.7	3500.4	3862.4	6861.7
Total system throughput (t km^{-2} yr^{-1})	17840.5	15891.1	17330.1	-	3026.3	9355.5	10866.0	23442.0	37497
Sum of all production (t km^{-2} yr^{-1})	8300.1	6972.6	7810.7	-	1330.8	4491.1	5315.0	10409.0	-
Mean trophic level of the catch	2.18	2.30	2.31	2.94	2.45	2.55	2. 6	2.1	-
Gross efficiency (catch/net p.p.) (%)	0.0013	0.0025	0.0024	0.0028	0.007	0.08	0.0011	0.0023	-
Total net primary production (t km^{-2} yr^{-1})	7792.2	6205.1	7187.0	2226.2	1132.7	4017.0	4715.6	9670.3	-
Total primary production/total respiration	3.81	2.16	2.64	-	1.44	3.198	3.12	1.35	1.367
Net system production	5746.23	3331.09	4461.02	-	345.1	-	3202.8	2482.2	-
Total primary production/total biomass	52.08	36.83	46.47	-	19.7	16.2	10.6	35.6	27.6
Total biomass/total throughput (yr^{-1})	0.0084	0.011	0.0089	-	0.02	0.027	0.04	0.01	0.011
Total biomass (excluding detritus) (t km^{-2})	149.6	168.5	154.7	110.3	57.6	248.6	444.8	221.8	-
Total catch (t km^{-2} yr^{-1})	10.07	15.51	17.11	6.133	8.08	3.01	5.12	22.11	-
Connectance Index	0.387	0.375	0.388	0.386	0.32	0.405	0.28	0.25	-
System Omnivory Index	0.119	0.111	0.087	0.193	0.12	0.289	0.12	0.03	-
Finn's cycling index (%)	2.8	6.1	3.8	-	-	2.23	-	-	-
Average path length	2.29	2.56	2.41	-	-	-	-	-	-
Detritivory to Herbivory ratio (D:H)	0.61	0.75	0.64	-	-	0.32	-	-	-
Ecopath pedigree	0.72	0.79	0.68	-	-	0.673	-	-	-
Reservoir age (yr)	33	36	45	60	24	59	52	>100	89
Surface area (km^2)	18.6	6.7	0.62	180	150	200	410	25	16.26
Mean depth (m)	6.6	5.9	2.7	10	3	9	5.5	5	3.6
Country	Ghana	Ghana	Ghana	C. d'Ivoire	B. Faso	Ethiopia	Thailand	Sri lanka	India
Climate type	Semi-arid	Semi-arid	Semi-arid	Semi-arid	Semi-arid	Tropical Arid	Tropical monsoon	Tropical dry	Tropical dry

[a]Traore et al. (2008); [b]Villanueva et al. (2006); [c]Tesfaye and Wolff (2018); [d]Villanueva et al. (2008); [e]Panikkar and Khan (2008)

Fig. S6.1. Monthly variation in water level, turbidity and Secchi depth (transparency) in Tono (A), Bontanga (B) and Golinga (C) reservoirs. The dashed red line represents the mean of measurements during the study period (July 2016 to June 2017).

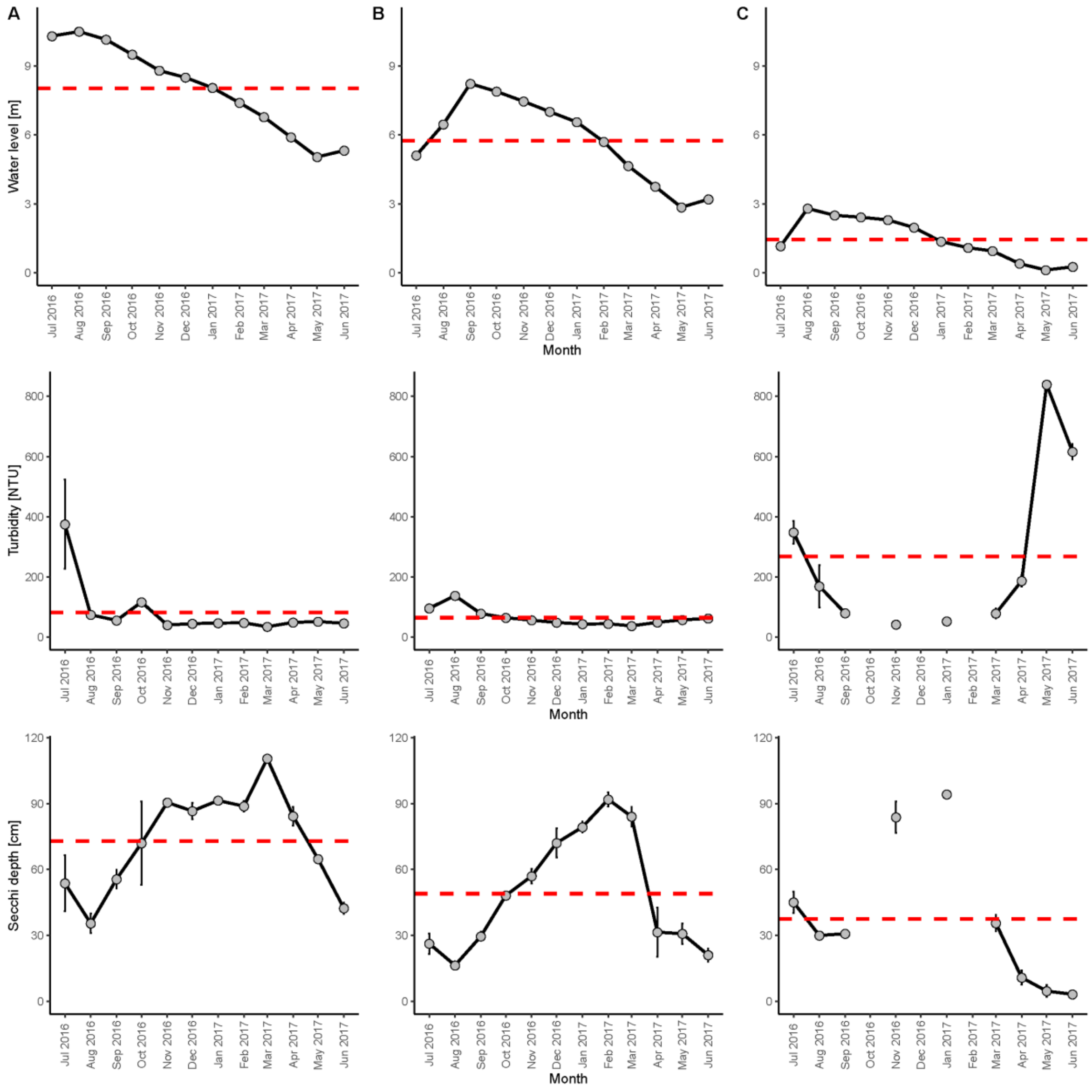


Fig. S6.2. Monthly variation in dissolved organic carbon (DOC) and total dissolved nitrogen bonded (TDNb) concentrations in Tono (A), Bontanga (B) and Golinga (C) reservoirs. The dashed red line represents the mean of measurements during the study period (July 2016 to June 2017).

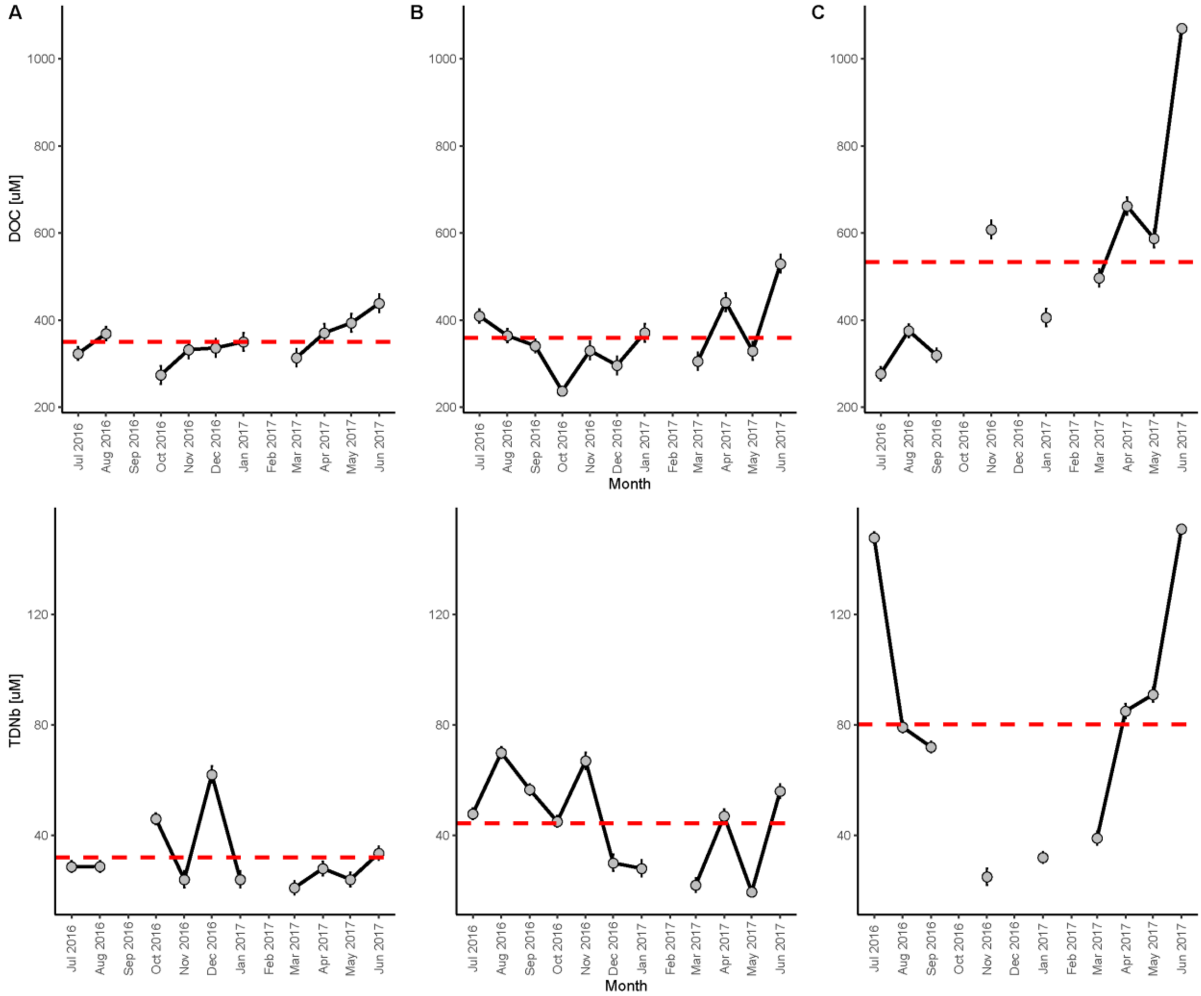


Fig. S6.3. Monthly variation in chlorophyll *a*, PO4 and Si concentrations in Tono (A), Bontanga (B) and Golinga (C) reservoirs. The dashed red line represents the mean of measurements during study period (July 2016 to June 2017).

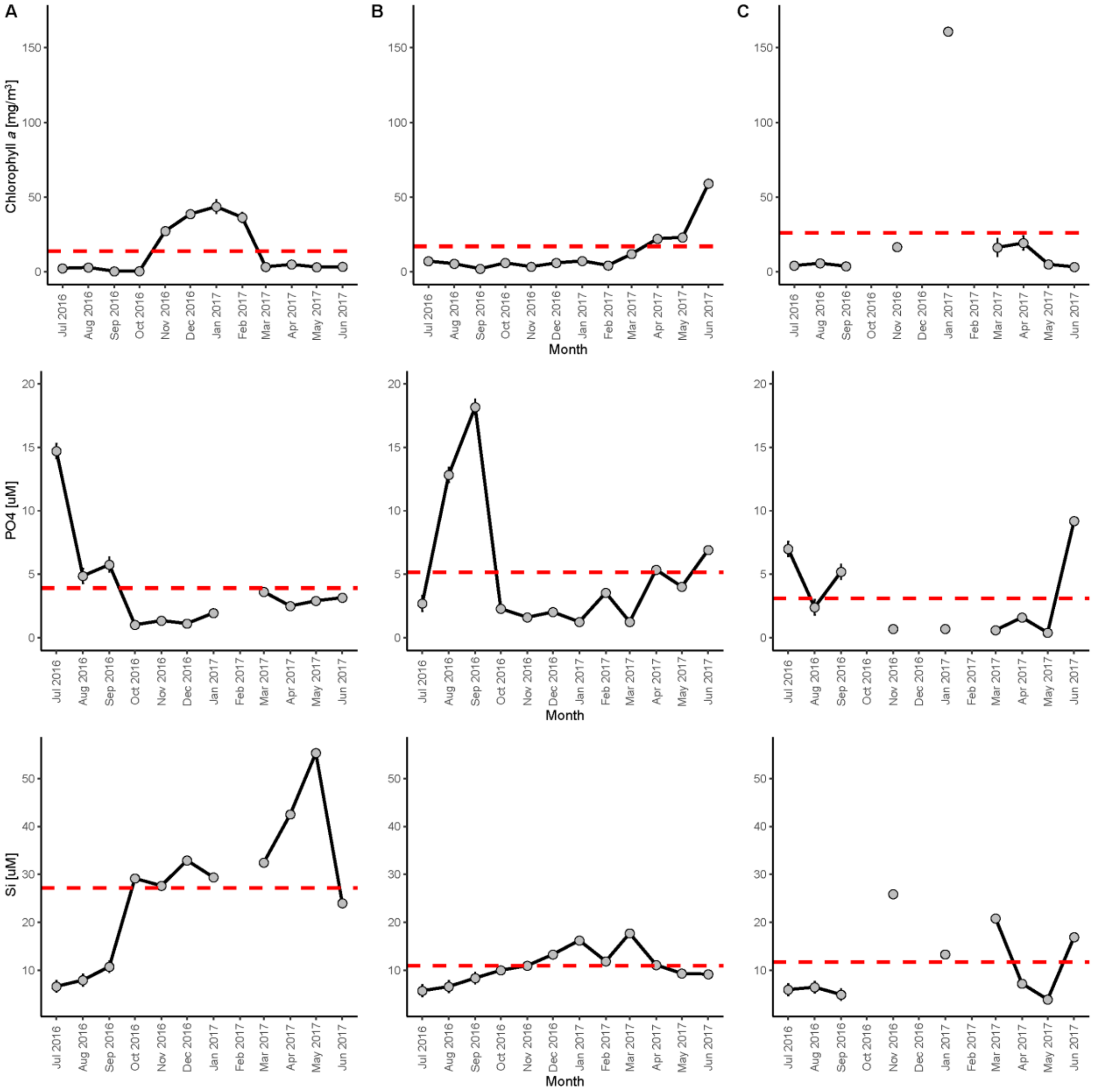
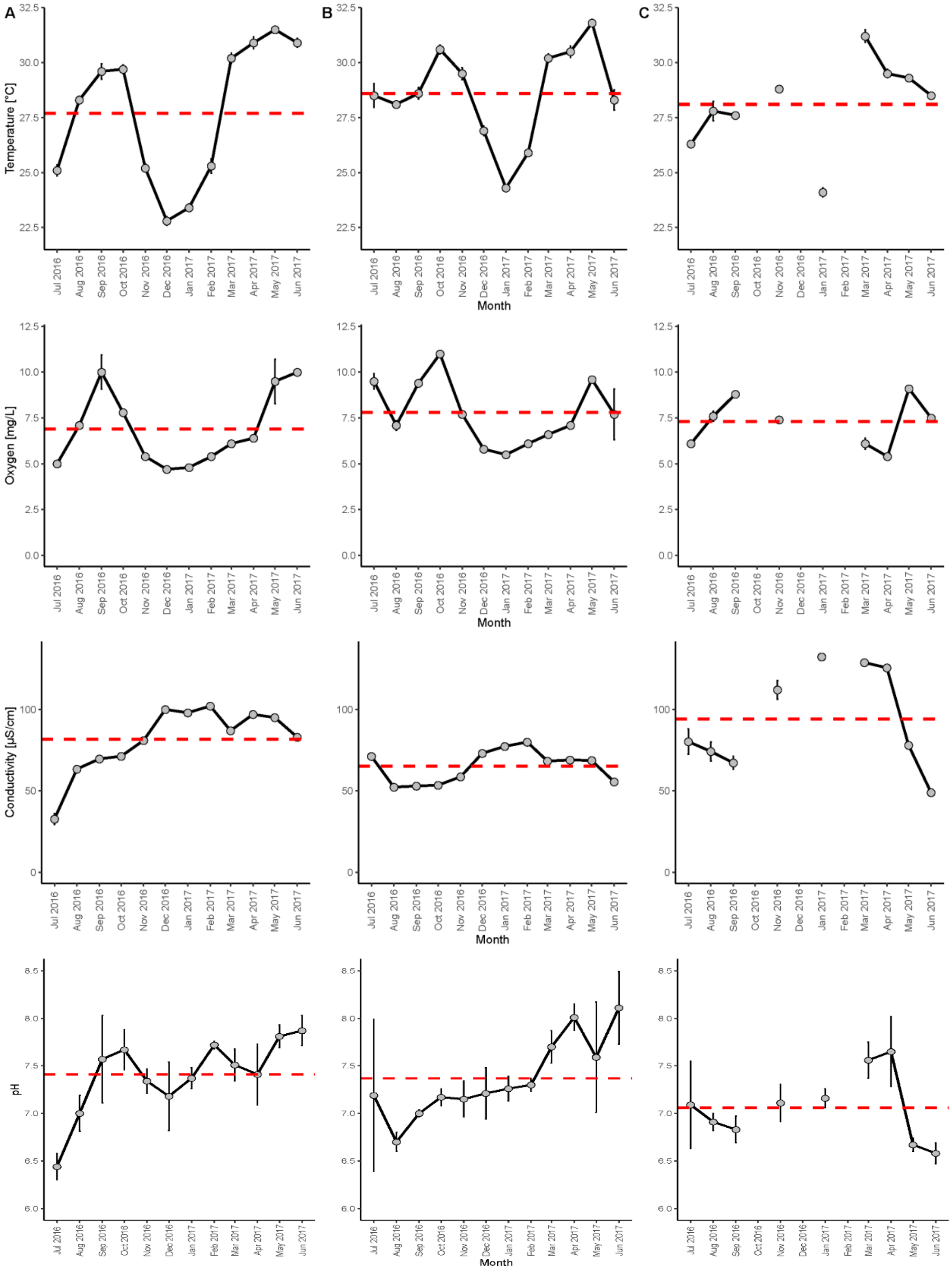


Fig. S6.4. Monthly variation in temperature, oxygen, conductivity and pH concentrations in Tono (A), Bontanga (B) and Golinga (C) reservoirs. The dashed red line is the mean of the measurements between July 2016 and June 2017



Manuscripts and author contributions

List of papers and author contribution

Paper 1

Abobi, S. M., Wolff, M., 2019. West African reservoirs and their fisheries: An assessment of harvest potential. *Ecohydrology and Hydrobiology*.

Contributions by first author (SMA): concept and design- 50%, data acquisition- 100%, data analysis and interpretation-80%, and manuscript writing and revisions - 80%.

Paper 2

Abobi, S. M., Stäbler, M, Wolff, M., 2019. Elucidating differences in environmental variables: implications for reservoirs fisheries management in northern Ghana. (*In preparation*).

Contributions by first author (SMA): concept and design- 60%, data acquisition- 80%, data analysis and interpretation-100%, and manuscript writing and revisions - 90%.

Paper 3

Abobi, S. M., Mildenberger, T.K., Kolding, J., Wolff, M., 2019. Assessing the exploitation status of main fisheries resources in Ghana's reservoirs based on reconstructed catches and a length-based bootstrapping stock assessment method. *Lake and Reservoir Management* 35(4): 415-434.

Contributions by first author (SMA): concept and design- 80%, data acquisition- 100%, data analysis and interpretation-70%, and manuscript writing and revisions - 70%.

Paper 4

Abobi, S. M., Oyiadzo, J.W., Wolff, M., 2019. Comparing feeding niche, growth characteristics and exploitation level of the Giraffe catfish (*Auchenoglanis occidentalis*, Valenciennes, 1775) in the two largest man-made lakes of northern Ghana. *African Journal of Aquatic Science* 44(3); 261-272.

Contributions by first author (SMA): concept and design- 80%, data acquisition- 100%, data analysis and interpretation-90%, and manuscript writing and revisions - 70%.

Paper 5

Abobi, S. M., Kluger, L, Wolff, M., 2019. Comparative assessment of biodiversity, food web structure and fisheries productivity of three man-made lakes in Ghana. (*Submitted to Freshwater Biology*).

Contributions by first author (SMA): concept and design- 60%, data acquisition- 100%, data analysis and interpretation-60%, and manuscript writing and revisions - 60%.

Conference and workshops contributions

- **Abobi S.M.**, J.W. Oyiadzo and M. Wolff. (2019). Feeding niche, growth characteristics and exploitation level of the Giraffe catfish (*Auchenoglanis occidentalis*, Valenciennes, 1775) in the two largest man-made lakes of northern Ghana. European Inland Fisheries and Aquaculture Advisory Commission (EIFAAC) International Symposium 2019: Food Safety and Conservation in Inland Fisheries and Aquaculture. Deutsches Hygiene Museum, Dresden, Germany, September 09-12, 2019. (Oral presentation).
- **Abobi, S. M.** and M. Wolff. (2018). Trophic networks of reservoir systems in Ghana. Ecological Network Analysis (ENA) Workshop. 19-21 September 2018, Leibniz Centre for Tropical Marine Research (ZMT), Bremen, Germany. (Oral presentation).

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