Fresh Water Fish Farming Suitability Assessment – Chad

Draft version

April 2023

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Abstract

The aim of this report is to document a fresh and warm-water fish farming systems suitability assessment for Chad, for the African Catfish and Nile Tilapia species. This aquaculture geographic information systems (GIS) multi-criteria decision analysis (MCDA) study goals are to support the Hand-in-hand Initiative and ongoing fish farming development and planning initiatives in the country.

The modelling methodology developed from Aguilar-Manjarez and Narh 1998 - A strategic reassessment of fish farming potential in Africa. The approach uses weighted factors including market demand, wealth index, infrastructure, inputs livestock and crops, physical geography (soil, slope, water availability) and potential yield. Modelling applies constraints or exclusive criteria distinctly to different farming systems: protected areas, densely urbanized areas, large water bodies, flood areas, distance to major roads and bank, and access to information technology and communications.

Results consist of a set of models, sub-models, and mapping outputs indicating the potential high return on investment optimal sites, aimed at intensive fish farming for both closed catfish (tanks, raceways, ponds, recirculating aquaculture systems) and open tilapia (water bodies) systems, and zoning at region and department scale directed at open non-intensive integrated pond systems, with potential impact on poverty alleviation, improving nutrition, and food security.

Results show intensive closed farming systems suitability spatial pattern centred around output markets, large metropolitan/urban areas: Most suitable score areas are in the south Sudanian agroecological zone (AEZ), in a Moundou centred zone, but also in southern parts of the Sahelian AEZ.

Final mapping emphasizes southern urban centres, Bongor, Pala, Moundou and Sahr, and a smaller area in Am Timan. Interpretation must consider data gaps, finance access (bank agencies) data might not be exhaustive, complete, and accessibility to urban areas, with smaller cities Abéche, Moundou and Sarh, weighting the same as the capital N'Djaména.

Tilapia open intensive systems in water bodies using open-net pens/ cage techniques, highest location score areas are to the immediate north of N'Djaména, around Moundou, and in small areas bordering Cameroun and the Central African Republic.

Large scale final location mapping using permanent waters, points to potential locations in lakes and major rivers:

- N'Djaména area and the Chari and Logone rivers bordering Cameroun.
- Lake Chad region water, wetlands, and the Chari River.
- Lake Iro.
- The Logone River in the northwest of the city of Bongor and close to the Maga reservoir.
- The Logone River, the Wey Lake in Moundou and Logone River in the south of Lai.

For the open non-intensive integrated fish/crop farming system, the highest potential areas are in the country's south Sudanian AEZ, Mayo-Kebi, Logone, Moyen-Chari, Tandjilé and Mandoul regions, with prominence to the east of the city of Moundou in the Logone and Mayo-kebi. Lower score but suitable areas are also in the southern Sahelian zone, in Guerá, Salamat and Sila regions. The northern two thirds of the country are unsuitable.

The location score filtered using asset wealth index (AWI) bellow national average classifies the lowest income suitable areas in south regions, and within smaller areas in the southern of Sahelian zone regions Guerá and Chari-Baguirmi. Mapping at department level mean values highlights the southernmost regions Mayo Kebbi Ouest, Logone occidental/Oriental, Mandoul and part of Moyen-Chari. The top location score districts are Lac Wey, Guéni, La Nya Pendé and Kouh Ouest.

Subtracting the normalized AWI to the location score defines a priority score. Priority mapping at department level draws attention to the southern Logone Oriental and Occidental, The Mayo-kebi Ouest, and southern areas of Tandjilé and districts of Mandoul. The city of Moundou appears central to a fish farming potential zone.

Fish farming development must consider sustainability environmental aspects, health and disease management and monitoring, but also to recognize ethnic and cultural diversity, land tenure and resource competition, and related conflict and security issues in the region.

Keywords: Aquaculture zoning; Aquaculture Chad; Aquaculture spatial analysis; Aquaculture zoning modelling; catfish tilapia zoning; catfish tilapia GIS

Acknowledgements

I would like to express my deepest appreciation to those who provided me the possibility to engage in this analysis and complete this report, CSI Karl Morteo and FAO SFC Lionel Kinadjian.

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INTRODUCTION

This report documents a freshwater fish farming Geographical Information Systems - Multicriteria Decision Analysis (GIS-MCDA) suitability assessment for aquaculture zoning and identification of potential sites in Chad.

Departure questions were formulated as:

1. *What are the regions and states where freshwater fish farming should be promoted for poverty alleviation, improving nutrition, and food security?*
2. *Where are the best sites for intensive commercial closed farming system investment?*
3. *Where are the best sites for intensive commercial Tilapia fish farming open systems?*

Research methodology follows previous Hand-in-Hand initiative analysis for value chain infrastructure location. A brief literature review on sub-Saharan Africa and Chad's fisheries and aquaculture fish-farming sector provides context, background, and perspectives. Modelling assumes a GIS-MCDA methodology applying weighted factors (AscoughII et al., 2019; Boroushaki & Malczewski, 2010; Malczewski, 2006).

Fish farming suitability/potential zoning modelling is based on specific sub-models, criteria, and spatial constraints. It builds from Aguilar-Manjarrez and Narth study on warm-water and temperate-water fish farming suitability in continental Africa ((Aguilar-Manjarrez & Narh, 1998)), a raster-based GIS-MCDA using fish-farm and land-quality factors, with sub-models and categories of criteria:

1. Constraints (urban areas, large water bodies, protected areas)
2. Water requirement
3. Soil and terrain suitability
4. Inputs – crops and livestock
5. Farm-gate sales - as a measure of population density classification.
6. Potential yields.
7. Urban market size and proximity.

Sector growth, data availability, and fish farming systems and technologies have evolved since the late 20th century. Some of the base data is updated, and sub-models, criteria weighting, and constraints are reviewed.

Two distinct zoning efforts are presented. The first at a broader scale, intends to identify regions and departments where investment can positively impact poverty, hunger, malnutrition, and food security:

- Extensive to semi-intensive small-scale integrated farming systems.

The second pursues the location of high return on investment sites for intensive commercial aquaculture systems, for both:

- Catfish closed intensive farming systems.
- Tilapia open intensive farming systems using cages in large water bodies (LWB).

Separate zoning efforts are developed for each farming systems or model, based on specific farming system theory, implying distinct criteria combination and weighting, and conditioned by a diverse set of constraints.

Three models were developed for:

1. Open non-intensive integrated fish/crop farming systems using ponds or small waterbodies.
2. Catfish closed Intensive systems – using closed/semi-closed-circulation technologies: recirculating tanks, raceways, flow-through systems, and ponds.
3. Tilapia open intensive systems in LWB – using net pens/cage techniques.

The models use physical geography conditions, supply, demand, infrastructure/accessibility, in the following criteria:

1. Physical geography
    a. Water requirement and seasonality
    b. Soil
    c. Terrain suitability (slope)
2. Supply
    a. Feed - crop production (Fischer et al., 2012)– crop by-products.
    b. Livestock – animal density (Robinson et al., 2014) – livestock by-products.
3. Demand - Human population density and large urban/metropolitan areas.
4. Infrastructure - Transportation network (accessibility).

The transportation network infrastructure is modelled as raster-based travel time/cost analysis ((Mulrooney et al., 2017) and accessibility/infrastructure travel time/cost to market is processed for large urban areas.

Applied constraints (depending on specificities of the farming system):

1. Urban Areas.
2. Protected Areas.
3. Large water bodies.
4. Flooding areas.

Final mapping exclusive criteria for intensive closed systems:

1. Distance to major roads.
2. Access to IT - mobile broadband coverage.
3. Access to finance – distance to bank agency.

The project is developed using open-source GIS software QGIS 3.22.9-Białowieża and mostly publicly available open-data sources[1].

This document is structured in 5 main sections: 1. CONTEXT AND BACKGROUND, 2. FISH FARMING ZONING MODELLING, 3. DATA PREPARATION; 4. CRITERIA SUBMODELLING - GEOPROCESSING; 5. SUITABILITY MODELLING, with INTRODUCTION and CONCLUSIONS presenting closing remarks on assumptions and possible pitfalls, results, and recommendations.

[1] Exceptions for AtlasAI (population density and asset wealth index) and Collins Bartholomew's Mobile Coverage Explorer data (from which a mobile broad band coverage data is derived).

GIS MULTICRITERIA DECISION ANALYSIS

Spatial decision problems involve a set of geographically defined alternatives and multiple and sometimes opposing assessment criteria. Alternatives are commonly assessed by many intervenient (decision-makers, stakeholders, interest groups).

GIS multicriteria decision analysis GIS-MCDA consists of a method to convert and combine spatial data/geographical information and decision-makers criteria to attain evidence for a decision-making process. GIS capabilities are enhanced by MCDA procedures, techniques, and algorithms for structuring decision problems, to design, evaluate and prioritize alternatives.

Integration of GIS and MCDA provides a replicable model, improves communication between project participants or decision-makers, can offer a unique perspective of problem and solution, helping to redefine initial specification and/or criteria.

GIS multicriteria analysis methods are usually presented in a three-stage hierarchy of: intelligence, design, and choice.

In the intelligence phase, data are acquired, processed, and exploratory data analysis is performed.

The design phase should entail the formal modelling/GIS interaction development of a solution set of spatial decision alternatives. The integration of decision analytical procedures and GIS functions is critical for supporting the design phase.

The choice phase involves selecting location alternatives from those available. Specific decision rules are used to evaluate and rank alternatives.

The three stages of decision making do not necessarily follow a linear path.

From a critical standpoint it can be stated that, while quantitative data analysis and evidence gathering through GIS modelling certainly contributes to attaining evidence for decision-making processes. It is a complex set of socio-economic, political, cultural, ethno-anthropological aspects, and power relations which shape processes and govern decision-making.

Modelling is as good as the input data. Its quality and reliability support the extent to which conclusions can be trusted, and these are just as sound as the analysis conducted. From that prism, specification and objectives define modelling assumptions and approximations and can always produce distinct answers ((Kitchin, 2014b).

Data are both social and material do not just represent the world but can actively produce it, are not mere raw material of information and knowledge, do not exist independently of ideas, techniques, technologies, people, and contexts that produce, process, manage, analyse, and store it. Positionality is always present even when “data speaks for itself” (Kitchin, 2014a).

1. CONTEXT AND BACKGROUND

OECD-FAO Agricultural Outlook 2021-2030 projected world fish production to grow at 1.2% and aquaculture at 2.0% p.a. in the decade. Lower aquaculture production growth rates than previous decades reflect policy changes in China (sustainability and environmental protection), feed cost, reduced productivity gains, and competition for land. By 2030 aquaculture will supply 57% of human fish consumption overtaking capture production by 2027.

SUB-SAHARAN AFRICA

The population of the Sub-Saharan Africa (SSA) region was 1,106,957.90 in 2019, and with an annual growth rate of 2.5 % projected to reach between 1.5 and 2 billion by 2050. Unemployment rate was around 6.1% for the same year. Although poverty headcount ratios, in percentage of population, have fallen from over 60% in the 1990s to close to 40% in 2019 there are great disparities between countries and subregions (World Bank[2])

Per capita fish consumption in Africa is projected to decrease as the fast-growing population outpaces the growth in production.

Aquaculture production in SSA takes place essentially inland and in freshwater. Operations found are subsistence, small-scale market-driven, and large industrial scale. From 2004 to 2014 there was a seven-fold increase in production with an average percent growth rate (APR) of 2%. The first sales value of the 2014 production was US$1.6 billion, mainly of indigenous ubiquitous species of tilapia and catfishes. Seven countries (the Federal Republic of Nigeria, the Republic of Uganda, the Republic of Ghana, the Republic of Kenya, the Republic of Zambia, the Republic of Madagascar, and the Republic of South Africa) concentrated 93% of production (Satia, 2017).

The sector experienced a steady growth based on indigenous species, genetic and feed improvement, government, and development agencies support and a large growing demand.

Some of the commonly identified constraints and risks miss supporting data and are poorly assessed in existing literature: environmental impacts and health/food safety related, social impact, land and water competition, employment, value chain growth and risks like climate change impacts or social, ethnic, and regional conflicts are also merely mentioned.

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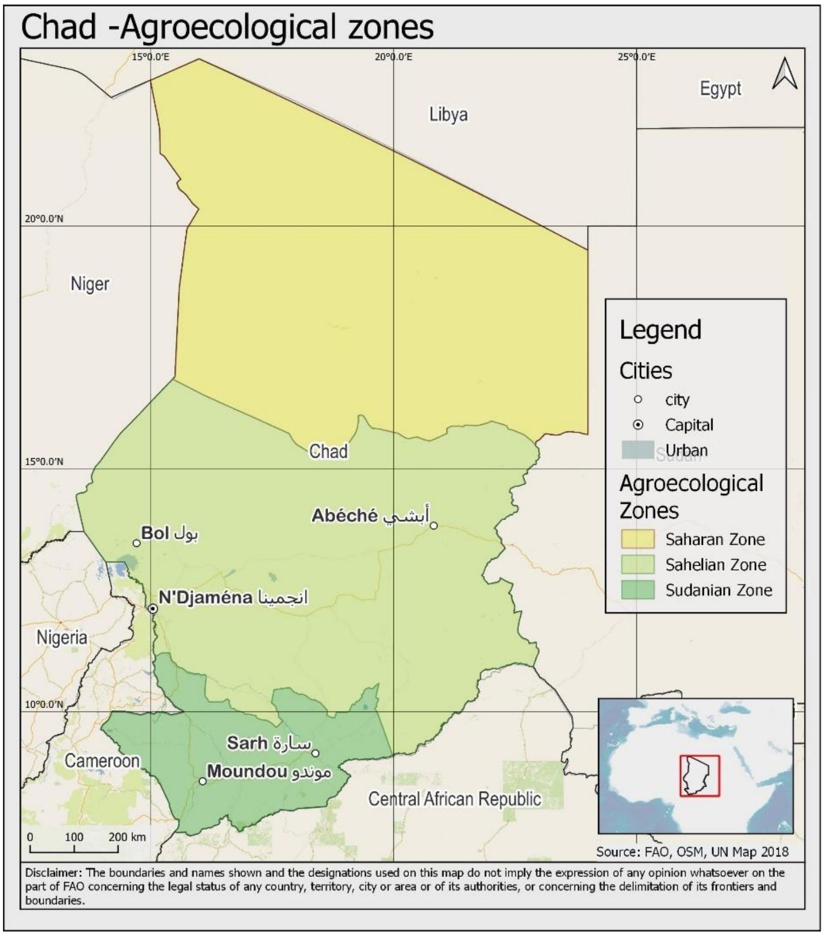
[2] https://data.worldbank.org/indicator/SP.POP.TOTL?locations=ZG

Recent fish farming growth is framed by an increasing importance for improving food security, job creation, economic growth, and resource use, supported by external assistance from FAO and other development partners, donor organizations and investors, and a growing private sector participation.

CHAD

Located in Central Africa south of Libya, bordering Cameroun, Central African Republic, Libya; Niger, Nigeria, and Sudan, with an area of around 1.284 million km², Chad is one of the worlds most landlocked countries.

According to FAO Crop Calendar[3] The country is divided in three major agroecological zones (AEZ), the mapping follows the administrative division regions into the AEZ.



The Sudanian Zone covers about 10% of the country, it has a long wet season (3 to 6 months) and a dry season (mid-April, mid-October), rainfall varies from 800 to 1200mm/yr. Production systems

[3] FAO Crop Calendar - Information Tool for Crop Production https://cropcalendar.apps.fao.org/#/home

are diverse with association of cereal crops, pulses, oilseeds, cotton and tubers to livestock transhumance.

the Sahelian Zone represents around 43% of the territory, average annual rainfall is between 200 and 700 mm, with a longer dry season (8 to 9 months) and short rainy season (July to September). Production systems are agropastoral, combining rain-fed farming to livestock transhumance (small ruminant flocks of cattle and some camels). The main production systems are flood recession crops, rice cultivation, wheat, and corn with or without water systems control and cultivation of millet on the dunes forming a hinge zone or transition to the Saharan systems.

The Saharan desert and arid climate correspond to 47% of the country, with under 200 mm average annual rainfall, which can be brief and violent for two months (July and August). The AEZ is characterized by oasis date production, combining to irrigated subsistence farming, small sedentary livestock, and transhumance camels. Subsistence farming is practiced in understory palm (fruit, wheat, millet, vegetables, etc.)

Fishing is practiced in major Lakes and floodplains, the major fishing area is the endorheic Lake Chad and the Logone/Chari floodplain that feed it, but it also takes place in other smaller but important lakes like Lake Fitri (800 km²), Lake Iro (110) km² and Lake Léré (40 km²). According to FAO Fishery and Aquaculture Country Profiles (FAO, 2023) Chad's river system is the habitat to about 177 species of fish, 30 of which are commercially exploited. National authorities' data, shows total catches reached more than 107 000 tonnes in 2017.(FAO, 2023) [4]

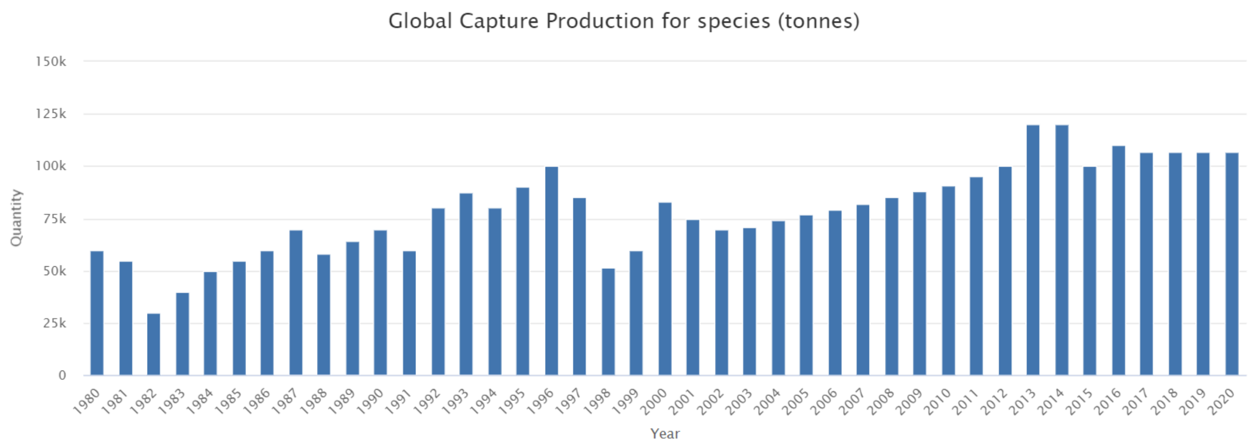


Figure 1 – Fisheries global capture production - source: FAO Fishery and Aquaculture Statistics

[4] FAO fishery and Aquaculture Country Profile https://www.fao.org/fishery/en/facp/tcd?lang=fr

Capture production is stable around the 100 thousand tonnes for the last decade, with variations reflecting differences in precipitation that impact the lakes area and fish availability.

There is a clear production consumption gap, FAO estimates 2017 exports of fish and fishery products at USD 46 000 and imports at USD 1.2 million.

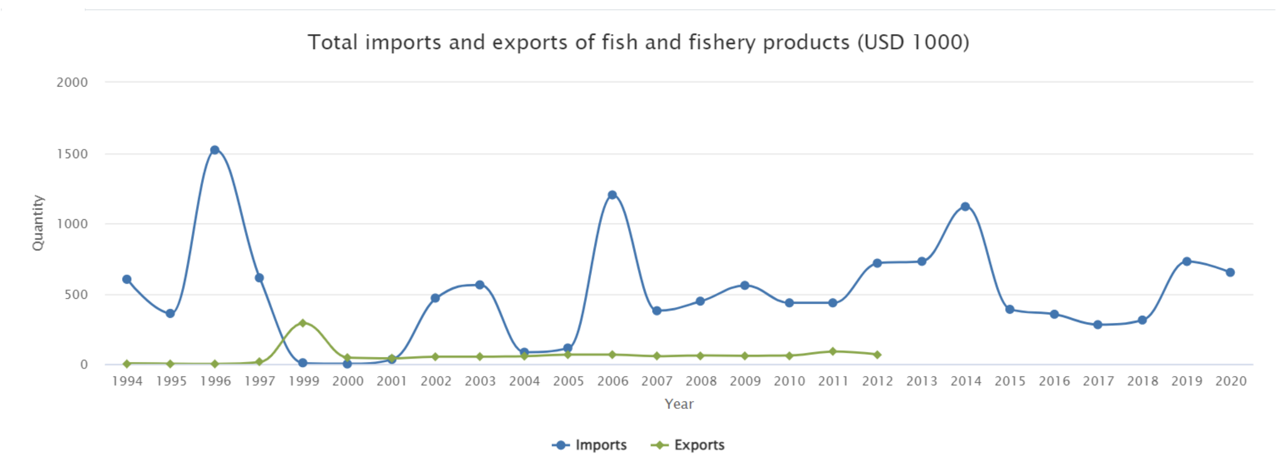


Figure 2 - Fisheries imports and exports (USD 1k)

Chad is a net importer of fish and fishery products.

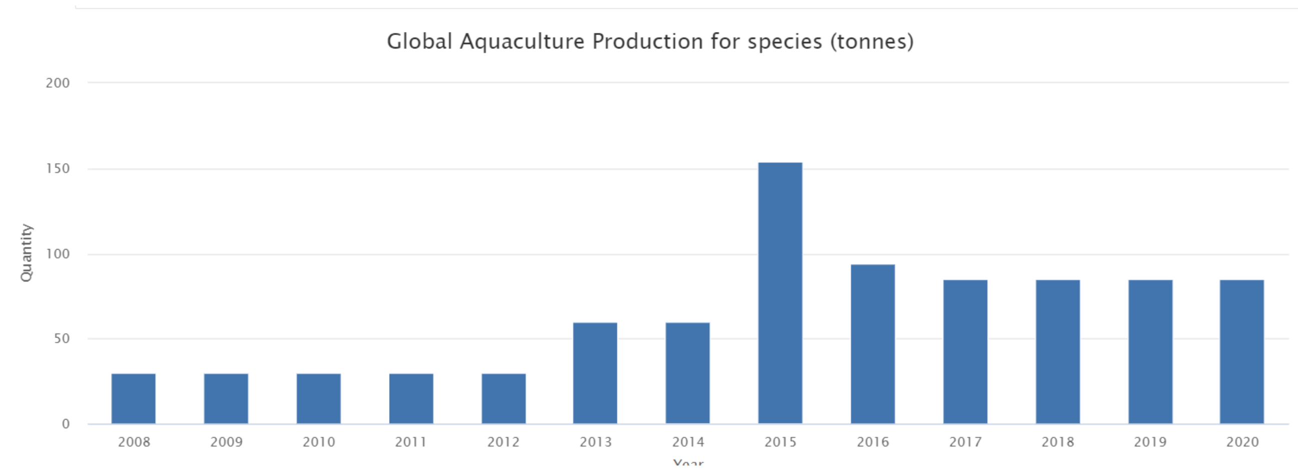


Figure 3 - Aquaculture production

Aquaculture production remains limited in 2017 having produced about 430 tonnes, near half of it destined to export to Cameroon, the Central African Republic and Nigeria.

Women control processing, preservation and marketing, and traditional processing techniques are the smoking and drying. The annual per capita fish consumption was around 7.7 kg in 2016 and the contribution of the fishery sector to the national economy estimated between 1.3 and 4.5 percent of GDP.

In 2017, just under one hundred people were estimated to be employed in aquaculture. In the inland fisheries, 44 percent of the employees were women out of a total of 435 000. In 2017, there were 21 700 small non-motorized boats estimated.

In 2010, the Government of Chad with the support of FAO, established a Strategic Framework for Aquaculture Development and created the Department of Fisheries and Aquaculture (DPA) within the Ministry. Environment and Fisheries Resources (MERH). The National Strategy for Fisheries and Water Resources focuses on: (i) fisheries development; (ii) the promotion of aquaculture; (iii) water resources and meteorology; and (iv) sub-sector management.

Guiding the implementation of the 2010 "Strategic Framework for the Development of Aquaculture in Chad" FAO has supported the National Aquaculture Development Plan (FAO, 2012) focusing on the development of commercial aquaculture targeting food security and sustainable economic development (FAO Project TCP/CHD/3302) (FAO, 2012)

The plan defines areas with high aquaculture potential and an investment plan:

1) the N'Djamena area (hinterland of N'Djamena, Baguirmi, Hadjer Lamis),
2) the Moundou area (regions of Logone Orientale and Occidentale and Tandjilé Ouest) and
3) the Bongor area (East and West Mayo Kebbi region).

The plan objectives were:

1) Promotion of extension services, training, and capacitation.
2) Demonstration of the viability of aquaculture production systems.
3) Structuring the institutional and economic environment for the development of commercial aquaculture.
4) Establishing new modes of governance devoting the professionalization of the sector and the principle of public/private partnership, and
5) Capitalizing on the country's niche production (spirulina/dihé)

A key element of the Plan is human capacity building in, support and advice, extension, research, and training.

New modes of governance aim at solving issues related to production of fingerlings and feed, marketing, and the professionalization of the sector.

Because of accessible technical itineraries and potential economic profitability, pilot farming demonstrations target tilapia Oreochromis niloticus and catfish Clarias gariepinus using earthen pond systems as a priority. Trials were also planned for rice-fish farming and of tilapia in floating cages and ponds. The plan also focusses on the spirulina production sector due to its importance for women in rural areas, and aiming at improving the traditional *dihé* sector with the development of controlled production of production in artificial basins.

LAKES

Wetlands cover more than 10% of the Sahelian territory, with five main flood plains: the Senegal, Niger river delta, lake Chad flood plains, the Sudd swamps in South-Soudan and the Gambella in Ethiopia. These wetlands concentrate biodiversity, supply abundant water resources, fish, harvested products, grazing land and flood recession farming land.

Between 12,000 and 5,000 years ago Chad region had a green landscape, pastures and trees, numerous lakes, and large river networks, with the Mega Lake Chad being around 25 times larger than today, more than 350,000 km2. Archaeological findings in the hyper-arid Saharan agroecological zone, like images of boats and fishing scenes, show that in the middle Holocene resources favoured cultural groups whose subsistence depended on the wetlands (Gauthier & Gauthier, 2019). Extensive evidence of pastoral societies is present in Lake Ounianga rock carvings with a large diversity of both wildlife and domesticated livestock in the neolithic period (Gauthier & Gauthier, 2019; Mourre et al., 2019).

From the 1970s and 80s large scale irrigation developments have impacted the mobility, the multi-activity, and the multi-functionality of space in Sahelian wetlands, and the resilience of socio-ecosystems characterized by extreme climatic variability. Those investments brought new technical skills, new social organization, allocation and redistribution of land and family labour, which are among its failure factors. (Raimond, 2019)

In a competitive and conflictual context also marked by climatic deterioration, the Sahelian wetlands continued to sustain migrations, further disturbing socio-ecosystems. During the period, political options were limited to ineffective technical proposals from the post-independence.

Extreme droughts in the 1970s and 80s increased the lakes importance to agriculture and livestock in areas where production systems were based on the mobility of activities and labour, and defined by the tempo and level of seasonal floods.

In the region, customary, traditional, territorial governance is central to natural resources regulation and access, defined by the interrelationships between ecological and hydrographical processes, social organization, and cultures. In Chad, some of the smaller lakes are completely included into territories regulated by a centralized and hierarchical chiefdom power regulating access rights: Fitri (800 km²), Léré (40 km²) and Tréné (7 km²).

Since 2009 **violence** and military repression impacted development and relations between societies and their environment: Refugees, populations displacement, disappearance of economic outlets and changes in herd routes.

LAKE CHAD

Lake Chad drainage basin covers around 8% of the African continent (2,400,000 km2), its main contributor is the Chari River basin (610,000 km2) with major tributary the Logone River, smaller tributary the Komadougou Yobé (174,000 km2 subbasin), supplemented by the small basins of El Beïd, Yedseram and Ngadda in Nigeria (around 30,000 km2).

The Chari River supplies 85% of the surface water, and a 10% decrease of rainfall in its basin implies a 30% variation of the flow and in the lake. The lake divided by a natural barrier separating the southern and north basin, filling of the northern basin is random and variable. Water losses from the lake are by evaporation. (Sylvestre et al., 2019) The northern basin can retain water all year round like in the "Regular Little Lake Chad" current period, or dry up for a brief time (1985, 1987, 1988 and 1991).

Climate evolution since 1950 has seen a wet period till 1970, a dry period from 70s to 90s and an average period starting from 1995 to the present day, with improved hydrology and ecosystem services and yearly flooding of the northern basin. (Magrin & Lemoalle, 2019)

The population within a radius of around 300 km is forecasted to increase from 13 million in 2013 to 35 million in 2050: that of the basin from 50 million in 2013 to almost 130 million in 2050.

Diversity of resources and seasonal fluctuations, plurality of actors and complexity of rights of exploitation are competing reasons explaining the high conflict potential in Lake Chad region (Abdourahamani & Mato, 2019).

Fisheries in the northern basin

Fishing in Niger is extremely productive and practiced by Chadian, Malian, Nigerian and Cameroonians fisherfolks that represent more than 55% of the population. Fisheries is a major contributor to regional economy but highly dependent on strong hydrological constraints and resources unpredictability.

Migrant fisherfolks introduced techniques like the *doumba* (trap line) rapidly increasing fishing yields, used blocking waters between two shores, managed by a fisher (*ouban doumba*), paying the canton chief representative an annual amount. The *doumba* systems contributed to further appropriation of land, pond, and water.

Both state government and customary authorities regulate fishing access. The State issues permits, controlled by customary authorities represented by canton chiefs (*Maï*) that rule allocation of access rights. (Kiari Fougou & Lemoalle, 2019). Chiefdom *boulama* (mostly *Boudouma* ethnic group) control access, and there are reports of illegal taxation by soldiers and other agents of the state. Unequal rights of access to fishing favours autochthone groups and wealthiest fishing households.

While the traditional management system works well regulating fishing activity, it creates socio-economic distortions. The development and management of fisheries is complex, requiring participation and principles of co-management, certain characteristics must be considered:

- There are no practical means to enforce rules and compliance.
- There are overlapping hierarchy and governance (State/customary).
- Unpredictability/variability of the hydrology and fishery resources.

Existing governance and regulations seem unfitting, in one hand State management defines rules concerning access, but does not integrate variations in water, on the other hand traditional management considers local ecological situations but is often ambiguous about equal access. This calls for rules and means adapted to the different ecological zones, which can be effectively applicable in a transparent way.

Conflict

Since the 2000s, the return of water to the northern basin, favoured agricultural, pastoral and fisheries development, but precipitation irregularity and the interconnectivity of activities implies a complex management of access rights. In the context of growing attractiveness, a security crisis develops amplifying existing tensions (Abdourahamani & Mato, 2019).

There is a strong ethnic diversity in the Niger shore of Lake Chad, the most important groups are the *Boudouma*, the *Kanouri*, the *Toubou*, the *Fulani* and the *Arabs*. Autochthones *Boudouma* and the *Sougourti* are traditional breeders of the *kouri* cow (Mpofu & Rege, 2002) and Lake Chad is their traditional socio-political space. Strongly ethnocentric (Riera, n.d.), regularly plundering the shores, the group assured domination of islands and floodplains for centuries, never submitting to the Bornu empire[5], the raids of the *Tuareg*, *Toubou*, *Arabs*, or the colonial administration.

The *Fulani* are increasingly attracted to both recession grazing and farming land and occupy the hinterland pastoral basins, raising red zebus. Settled in eastern Niger after the 1914 drought, by the French colonial administration, in an area formerly travelled by the *Toubou* and the *Shuwa* and *Ouled Sliman Arabs* transhumant, disrupting the territorial hold of the latter.

Additionally, there are also migrant farmers, mostly Hausa, who are attracted by the flood-recession farming.

Competition for access and control of resources of Lake Chad in Niger have increased tensions between herders, and specially revived a *Fulani* and *Boudouma* conflict.

Lake Chad has long been a focus of ethnic conflicts in eastern Niger (e.g., The Fulani and *Toubou* between 1985 and 2000; *Boudouma* versus the *Mobeur* people of Bosso, when the Bosso chiefdom installed representatives allocating land to Bosso people and Hausa migrants). The Boko Haram crisis (beginning of the 2010s) and later the Islamic State West Africa Province (ISWAP) catalysed on conflicts intensified by the return of water to the northern basin, by a large population differential between *Hausa* and *Mobeur* migrants and the *Boudouma*, and by the *Fulani* exploiting flood-recession pastures.

Lake Chad regional settlements were disrupted by the insurrection and its repression causing 2 million refugees. Islands were displaced of most their populations, grouped in camps, villages, and settlements. Meanwhile, evacuated lands were occupied by new actors - in Nigeria the government authorized *Arab* herders to replace native *Boudouma* thanks to their anti-Boko Haram

[5] https://thinkafrica.net/kanem-empire/ , https://en.wikipedia.org/wiki/Kanem%E2%80%93Bornu_Empire

militias – and there was a forced shutdown of the economy of the lake caused by the evacuation of the most productive areas and the prohibition of certain commercial exchanges.

Groups of pastoralists and herders face increasingly problematic transnational mobility while at the same time search for new spaces, developing strategies to justify and legitimize actions, communities organise in self-defence militias, normalising violence and extra-judicial vigilante justice, that’s the context to *Fulani* and *Mohamid Arab*, *Boudouma* and *Kanouri Sougourti* conflict, capitalized by politico-religious radical movements and by integration efforts into the national space.

The return to abandoned areas and regulation between former rights holders and new occupants is an essential issue in the post-crisis period (Magrin & Lemoalle, 2019).

Another scale of power relations and actors come into the complex equation, economic agreements separated and parcelled vast areas, to development projects of the Komadougou Yobé basin and Lake Chad of approx. 120,000 ha by the Saudi company Al Horaish, oil exploitation by Chinese National Petroleum Company and Nigerian Petroleum Development Company initiatives (Iocchi, 2020).

The intensification of resources competition puts in check stablished dispute-settlement practices and community-level authorities, who are increasingly incapable to respond to the advance of a wide range of interests by growingly powerful actors.

In the Cameroonian Chad the multi-use of space territorial development supported demographic densification and the economic activity intensification. Natural resources governance made possible an exceptional economic development, based on a mode of governance with fluidity of forms of coordination between users and the absence of exclusion. (Rangé, 2019)

In Cameroun, the vast recession cropland that resulted from the drop in the lake water level were extensively colonized, turning the lake shores into densely populated and cosmopolitan areas. Until the security crisis the southern lake shores exported large food surpluses to the urban markets.

In sub-Saharan Africa, rights to resources are usually based on affiliations (lineage, ethnic, statutory) in the Cameroun Chad no group enjoyed exclusive control over water or land. From the 1970s the local Kotoko people Sultan claimed control of the waters, setting up landing stages and installing representatives in agreement with the administration. After a brief period of free access, fishers, farmers, and breeders presented to customary authorities, all having access to land and natural resources regardless of ethnic or national affiliation. Principles of work creating rights and right to subsistence, combined with a shared migration experience and recognized equal legitimacy. Those principles set balanced forces, growing economic interdependencies and a dense network of inter-knowledge.

The absence of socio-ethnic criteria in access to resources was the basis of settlement providing the ability to adapt to major environmental and economic changes in the 1980s. Contrasting with the conflicts in other large Sahelian wetlands in the same decade and with complex ancient land control over pastoral resources.

From the mid-1990s, environmental change gradually reduced fields to swamps, causing a densification in farming at the same time when there was a fast increase in herds. These unprecedented challenges were bypassed by integrating farming plots into blocks leaving uncultivated space to livestock. The customary governance system maintained its authority – sultan, sub-prefect, land chiefs and representatives of herders – and coordination flexibility between farmers and breeders was central to the spatiotemporal reorganization of activities.

Another example of supra-village organization is building dykes delaying flood, blocking an entire arm of the lake to gain arable land, where benefited must participate.

From the mid-2000s, different dynamics catalysed conflicts in the lake region: technical change, pastoral pressure, farming densification, and political instrumentalization of land. From 2014, with the Boko Haram insurrection, a growing number of migrants, refugees and displaced, and a "militia-like" militarization of local governance, led to major reorganizations in power relations. This security crisis reinforced a trend to patronage, with land becoming the dominant political issue for the post-conflict period.

LAKE FITRI

The Fitri is a shallow (1.5 to 3 m) endorheic lake with its drainage basin entirely in the Sahelian zone, a hydrographic network composed of various irregular streams, the most important the Batha River (60% of inflows), has an extremely variable surface area.

Flood extents depends on irregular rainfall of its catchment area (Yalikun et al., 2019), the lake is characterized by a system of connected ponds with fish-rich aquatic vegetation, valued by livestock, and cultivated when the floods recede. Production systems are based on principles of mobility, multiactivity (fishing, agriculture, livestock) and multifunctionality of spaces. Flood plains provide multiple resources (water, fish, pastures, agricultural land, wood) essential for transplanted sorghum flood recession system (berbéré, Sorghum bicolour).

In the Fitri variability adaptation evident in the diversification of activities: flood recession berbere farming, rainfed farming, fishing, small livestock, market gardening, foraging of doum nuts and other food products, and temporary work in urban areas.

The wetland resources have been expanding since the 1990s, open water and swamps doubled since the historical droughts (1970s-80s) and provide resources to a growing human population (59,000 to 110,403 inhabitants from 1989 and 2009).

During the droughts farming concentrated and the lake attracted transhumant herds, but since the 2000s flood recession farming and pastures are increasing, expanding farming and market gardening, and impacting herd mobility. Water also brought an increase in fisherfolks migration and adding to that, recently gold miners started to flow into the region (2016).

Livestock has more than doubled since 1976, even though the natural pasture extensive livestock system suffers from a degradation of grazing areas consequence of a combination of climatic deterioration, agricultural and pastoral pressure, population growth and the growing number of livestock due to the sedentarization. (Béchir et al., 2019)

Flood recession crops have been in expansion: from 3,000 ha in 1987 to 56,000 ha in 2015, their overall rate of change is 1,780% (11% per year). But still, self-sufficiency in cereals faces variable water resources, expanding livestock pressure, and strong population growth (Kemsol Nagorngar et al., 2019).

Fisheries

Delimited aquatic spaces are territories in the political sense and so, disputed and claimed. From the 1970s fishing has undergone strong socio-economic changes, technical improvement, and expanding demand, translated to resource competition, conflicts, and sustainability challenges. Customary authorities introduced non-native fisherfolks to the various fishing territories and fishing tools and techniques have diversified (traps and nets).

Water territories maintain legitimacy and are reference for fisherfolks, but, while still strong and recognized, the Bilala Sultanat customary institution is progressively uncapable of dealing with environmental management, conflicts of use and the proliferation of actors (Saunier et al., 2019).

Environmental factors and fish processing techniques must also frame a fish farming suitability assessment. Evidence is found of inappropriate drying and smoking using agriculture pesticides, and storage conditions around the lake, where humidity is high, lead to elevated levels of mycotoxins. There is also an elevated level of heavy metals content in fishes and water, and agricultural and pastoral activities impact water quality and fish (animal manure, and pesticides), adding to organic pollution from domestic waste (FAO, 2009; Mikail et al., 2018; Oumar et al., 2018; Ousman et al., 2019)

While Lake Fitri region has strong halieutic, agricultural and pastoral potential, it is also highly vulnerable to flooding and faces rapid population growth. Recent infrastructure development promotes accessibility to profitable urban markets, and it can consist of an incentive to increase production.(Bémadji & Mbaye, 2019)

Land tenure challenges

Land tenure challenges are common to all Sahel and many sub-Saharan countries. The State owns the land, but customary lineage property management prevail in many areas. Bilala Sultanate territory includes Lake Fitri since the 16th century, and is managed by strong and centralized power that regulates activities and conflict resolution.

The land potential is defined by flood levels and access and exploitation governed by traditional rules based on collective and individual rights. The common land is guaranteed by a founding ancestor but without exclusive property rights. The land chief disposes unallocated land, but cannot sell it, property is collective at the family level and individuals benefit from usufruct. Rules are strictly respected and include fees and rituals to secure usufruct rights.

Recent demographic pressure, state actors and administrative reforms challenge the customary land system, introducing dualism of land tenure systems and conflict management. The diversification of authorities impacts transparency, feeds clientelism and corruption, and increases tensions between communities. In complex conditions, such as that of Fitri, State representatives' management can constitute a risk factor. (Mbagogo Koumbraït, 2019).

The traditional system resilience depends on the complementarity of activities and the recognition of customary authority, and its longevity built on the monopoly of rules and definition of access rights, possible due to resource availability, low occupation, and settlement homogeneity. But both endogenous change and growing external pressures challenge the traditional system to a point where it cannot deliver (Mugelé, 2019).

Rapid development and change are in place: demography, technical innovations, new economic activities, transformations in the practices and disruption of local socio-economic life. These materialize in migrant professional fisherfolks, growing demand from urban centres, growth of transhumant pastoralism and recent presence of artisanal-type gold panning. Anthropic pressure accelerates conflicts, and the traditional justice regulatory mechanisms are outdated. In parallel, other disputes to the legitimacy of the Sultanate appear to take place, from which the splitting off the historic canton of Fitri in 2016, into seven new cantons, seem to be evidence.

Lake Fitri represents the common political and environmental issues of Sahelian wetlands, where growing anthropogenic pressure questions the stability of the socio-ecosystem, weakening local frameworks, and at a moment where climate change prospects impose a revision of relations between society and environment.

AQUACULTURE PRODUCTION SYSTEMS

Three major production systems are predominant in sub-Saharan Africa – earthen ponds, cages and concrete or earthen lined tanks (Satia, 2017). Open systems cage farming (tilapia and catfish) in large water bodies are the most profitable, with low capital investment per unit of fish production. The less-costly pond non-fed systems are undeveloped but have high potential impact on food security and nutrition. Closed systems, recycling, and land-based pump systems, are still limited by lack, or unreliability, of energy supply.

Secondary Production Systems, dam, ponds, integrated systems, and aquaculture associated to rice still have a large growing potential.

The catfish *Clarias* species and their hybrids production are commonly divided in two major stages:

1. Fish hatchery—production of fingerlings and juveniles.

2. Pond culture—earthen/dug-out, concrete tanks, cage/pen culture, fibre tanks, intensive recirculation and FTSs (raceway).

Intensive catfish production in “Fish Farming Estate” model using Recirculatory Aquaculture Systems (RAS) is the most productive and successful in sub-Saharan Africa. (Obwanga et al., 2018). Nigerian cooperative, public/private, peri-urban aquaculture model using ponds or concrete tanks, is based on shared investment in management, security, development of hatcheries and high-quality fish feeds. (Miller & Atanda, 2011). The fish farm estates model cooperative management locates in peri-urban areas and has been fundamental in enabling access to credit.

The ‘fish farming village” results from both market factors and government intervention, farmers associations and government collaboration: FISON (Fisheries Society of Nigeria) and CAFAN (Catfish Farmers Association of Nigeria), and the Federal Department of Fisheries (FDF), also benefiting from international development agencies support.

Tank farming systems have an increasing importance, these techniques have lower construction and maintenance cost, allow scalability, and can be located inside house compounds, limiting climatic constraints, and improving security.

Integrated aquaculture systems in small holder farming can have a direct impact on poverty alleviation, hunger, and malnutrition. In general, those are considered more sustainable and environmentally friendly, based in reusing and recycling of crop by-products, helping land/soil regeneration, pushing the reuse of idle land, and contributing to natural fertilization when in combination with irrigation small water bodies (SWB) (Musuka & Musonda, 2013; Mwayuli et al., 2010; Oribhabor & Ansa, 2006; Rasowo et al., 2010).

Rice-fish integration brings benefits to subsistence farmers improving and diversifying nutrition and increasing income possibilities (Rasowo et al., 2010). Rice and fish are produced concurrently, enhancing crop productivity, and at the same time optimizing water, land, and labour resources. Small-scale decentralized hatchery, fingerlings production, in rice fields has been successfully tested. Since rice cultivars size and growth period are locally sensitive, its analysis implies field work in the identification of specific cultivars and the refining of potential areas.

Like with other small-holder and subsistence systems, rice and aquaculture integration interventions must consider socio-cultural or biophysical factors, like the educational status of farmers or the gender division of labour, and the rice paddy environment - temperatures, oxygen levels or water turbidity.

Investment in small water bodies and small holder fish farming must also be consistent with regional specificity, considering issues such as low productivity, elevated level of abandonment or seasonality, constraints in extension services, training, fish seeds fingerlings availability, feed cost, and poor marketing.

The lack of strong institutions, financial services, failing extension services, or seed, has forced development resources to change from targeting subsistence non-intensive to focus on intensive commercial systems. But even though the investment in subsistence small-scale farming has failed in the past, at least for a visible fast production/productivity growth, the reasons are frequently not clearly identified.

2. FISH FARMING ZONING MODELLING

The analysis adapts Aguilar-Manjarrez and Narh approach to modelling warm-water and temperate-water fish farming potential in continental Africa. The 1998 technical paper follows Kapetski work - Strategic assessment of warm-water fish farming potential in Africa (Kapetsky, 1994), in adopting a raster based geographic information system approach, multi-criteria decision analysis, using fish-farm and land-quality factors.

The original study implied sub-modelling the following categories of criteria:

1. Constraints -urban areas, large water bodies, protected areas (exclusive criteria).
2. Water requirements – precipitation, evapotranspiration, seepage.
3. Soil and terrain suitability – soils, slope.
4. Input – crops and livestock (manure).
5. Farm-gate sales - population density classes.
6. Potential yields - number of degree days within optimal temperature range *(*air temperature, wind speed).
7. Commercial farming modelling adds urban market size and proximity.

Current data availability allows updating to higher spatial resolution and disaggregation, and farming systems evolution imposes a revision of some sub-models, criteria/factor weighting, and constraints.

Original sub-models and models were adapted considering most farmed species, the African catfish, and the Nile tilapia, for commercial (intensive) and small-scale (semi-intensive/extensive) farming systems.

Those systems present distinct objectives and business rules, modelling based on specific system criteria, criteria weighting, and different constraints or exclusive criteria.

Small-scale, extensive to semi-intensive, pond integrated farming systems directly targets poverty alleviation, hunger, malnutrition, and food security. The overall objective is the identification of potential regions or departments.

For **Commercial intensive systems**, using open or closed aquaculture techniques, the objective is the classification of top high return-on-investment sites:

- **Catfish intensive closed-systems** uses closed-circulation technologies like re-circulating tanks, raceways, flow-through systems, and inland ponds, essentially utilizing constructed or assembled manmade materials.
- **Open intensive systems** consider tilapia pen/cage techniques in large water bodies (LWB). Where the main location factor is the existence of a reservoir or dam but are also dependent on high accessibility to input and output markets.

All modelling criteria, constraints, and steps is detailed on 4. CRITERIA SUB-MODELLING - GEOPROCESSING and 5. SUITABILITY MODELLING.

3. DATA PREPARATION

3.1 DATA GATHERING/SOURCES:

1. **Collins Bartholomew** - Mobile Coverage Explorer - raster data representation of the area covered by mobile cellular networks around the world.
2. **FAO**:
   - A strategic reassessment of fish farming potential in Africa (Aguilar-Manjarrez & Narh, 1998) data layers: Potential Yields and Soil Suitability.
   - Rivers of Africa.
   - Inland Waters of Africa.
   - Geo-referenced database of dams (Africa), Airports, Ports.
   - WaPOR water productivity precipitation an evapotranspiration timeseries (2009/20).
   - GAEZ Global Agro-Ecological Zoning version 4 (GAEZ v4).
3. **IFPRI Global Spatially-Disaggregated Crop Production Statistics Data for 2017 (MAPSPAM) -** https://data.apps.fao.org/map/catalog/srv/metadata/59f7a5ef-2be4-43ee-9600-a6a9e9ff562a
4. **GLW Gridded Livestock of the World** - GLW 4: https://data.apps.fao.org/catalog/iso/15f8c56c-5499-45d5-bd89-59ef6c026704
5. **HydroSHEDS (Hydrological data and maps based on Shuttle Elevation Derivatives at multiple Scales)** – DEM- Void-filled elevation raster (30 sec) (Lehner et al., 2006) - https://www.hydrosheds.org/page/availability
6. **OpenStreetMap -** http://download.geofabrik.de/africa.html
7. **UNEP-WCMC and IUCN (2021), Protected Planet: The World Database on Protected Areas (WDPA) and World Database on Other Effective Area-based Conservation Measures (WDOECM)** [Online], May 2021, Cambridge, UK: UNEP-WCMC and IUCN. Available at: www.protectedplanet.net.
8. **AtlasAI**

- Atlas AI Population Density (Africa, 2020)
- Atlas AI's Asset Wealth Index (AWI)

9. **Global Surface Water 1984-2021** (European Commission Joint Research Centre) https://global-surface-water.appspot.com/

3.2 EXTRACTION AND PRE-PROCESSING

Selection/edition by location and attribute, and creation of a country vector database *geopakage*[6].

1. ***OSM Road layer (gis_osm_roads_free_1.shp)*** – Selected by location and attribute to generate a major roads layer. A comprehensive description of the features can be found in (Ramm, 2019). Lack of data on road network conservation, quality, and speed limit for most of the network imposes a conservative approach.
   - Attributes fclass = 'motorway' OR 'trunk' OR 'primary'.
2. OSM Railways (gis_osm_railways_free_1.shp) – Selected by location.
3. OSM Point-of-Interest Layer (gis_osm_pois_a_free_1.shp) – Select by attributes to generate layer Banks.
   - Attributes: 'bank'.
4. ***OSM Places Layer (gis_osm_places_free_1.shp)*** - Selected by attribute to generate major human settlements layer.
   - Attributes: 'city'; 'town'; 'national_capital'.
5. ***FAO Data - Ports; Airports; Secondary Airports*** - csv file formats - FAO http://rkp.review.fao.org/geonetwork – selected by location for the country.
6. ***FAO Major rivers*** - Rivers of Africa derived from the World Wildlife Fund's (WWF).
7. ***FAO Inland Waters*** – Clipped by country boundaries.
8. **FAO Geo-referenced database of dams (Africa)**: Point layer clipped by country borders to be used in conjunction with FAO Inland waters and Google Satellite for production of a Nigeria Dams (polygons) layer.
9. **UNEP-WCMC and IUCN** (2021), Protected Planet: The World Database on Protected Areas (WDPA) and World Database on Other Effective Area-based Conservation Measures (WD-OECM): Datasets were Clipped for CMR, merged the several layers and overlapping polygons combined.

Data is edited extracted/clipped using country borders.

[6] http://www.geopackage.org/

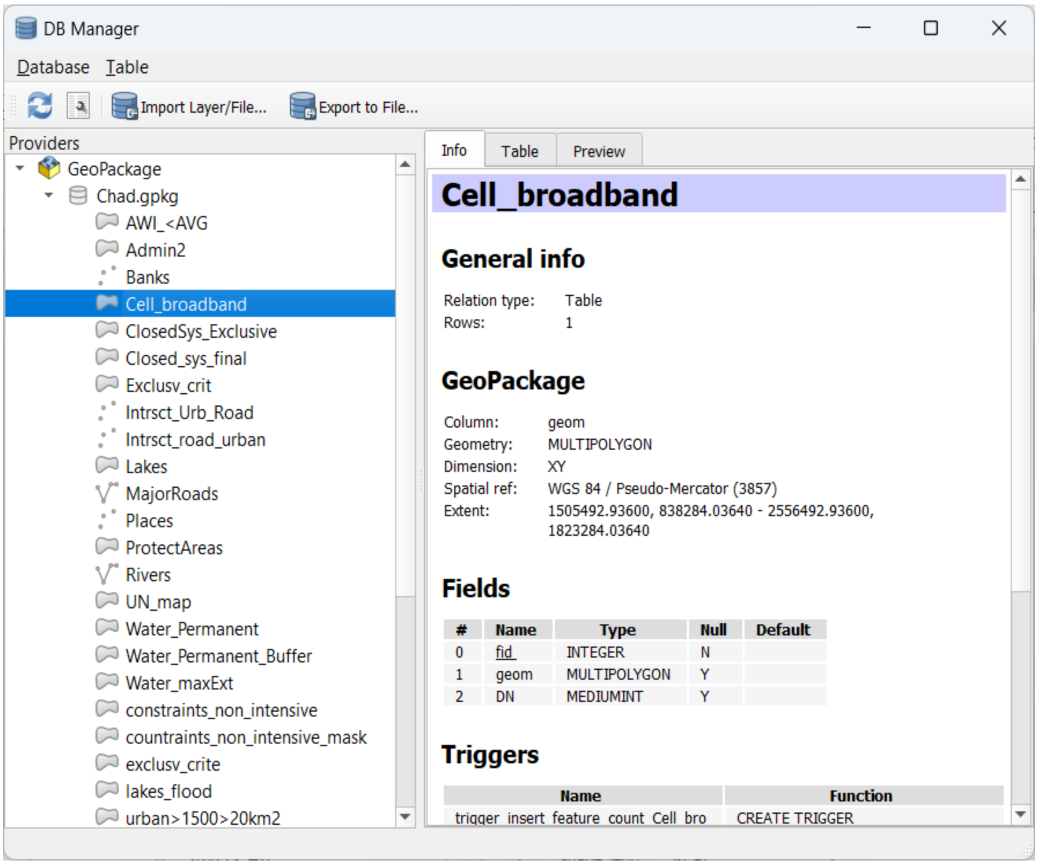


Figure 4 – Geopackage

4. CRITERIA SUBMODELLING - GEOPROCESSING

This section details modelling, editing and geoprocessing steps.

4.1 SUB MODELS: ACCESSIBILITY - INFRASTRUCTURE/MARKET

Accessibility data processing (travel time/cost surfaces) is based on the following assumptions:

1. Major urban areas: population density above 1500 habitants per square kilometre and a contiguous area larger than 25 km². Accessibility is calculated to major roads/major urban areas intersection points.
2. Lakes (inland waters) are represented by polygons; infrastructure network layers consist of linear features.
3. River navigation is considered only for segments with Strahler number > 7[7].
4. Road travel time/cost is modelled for primary/motorway/truck road classes; road network conditions are poor[8].
5. Lake and river navigation are treated as surface (polygons) not taking into consideration navigation infrastructure (points), it is assumed for small to medium cargo crafts.

The general steps to produce accessibility maps (travel time surfaces) are:

1. Rasterization vector layers.
2. Creation of cost friction surface.
3. Computation of a cumulative time/cost layer from/to points.

[7] https://www.jayconrod.com/posts/66/the-strahler-number

[8] https://dlca.logcluster.org/display/public/DLCA/2.3+Cameroon+Road+Network

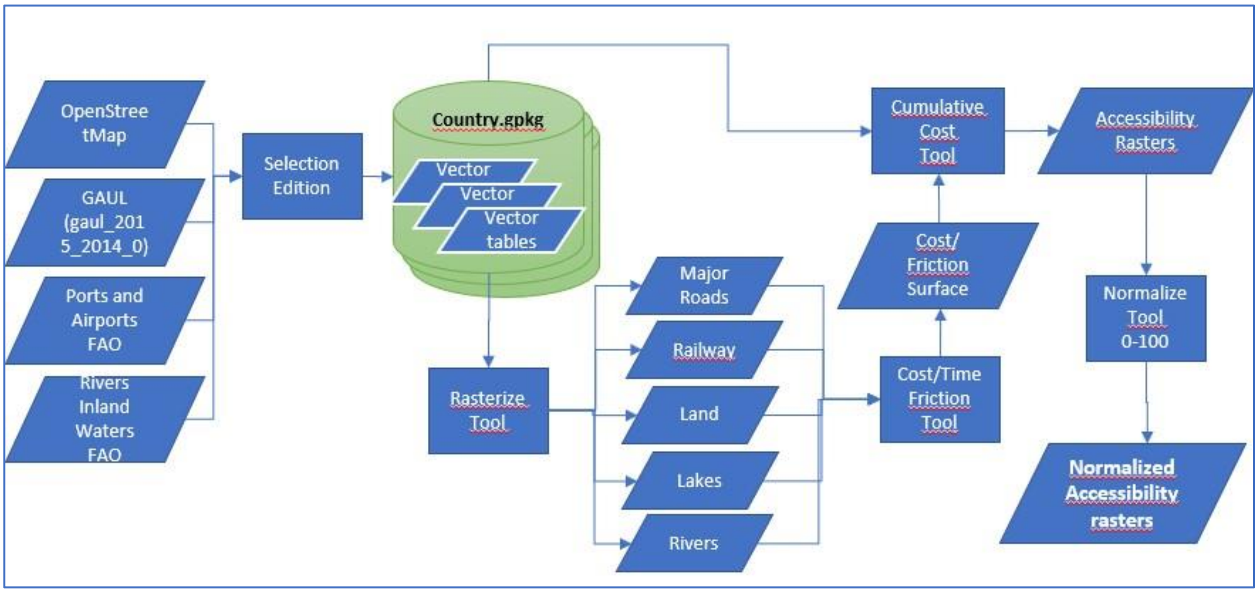


Figure 2 - Accessibility modelling flowchart

1. ***Rasterize*** **Tool** – Communication/transportation network and surfaces conversion from vector to raster, 1km cell grid burning a value for an average time (minutes) to cover a cell for the considered transportation mode ((a) land/walk, (b) major roads/vehicle, (c) railway/train, (d) navigation.

    - Modelling values:

Land (a)	10
Major roads (b)	1
Railway (c)	0.6
Navigation (d)	3

The rasterization outputs 1km raster grids with the modelling value per cell. Modelling value - speed - parameter can be changed/adapted to a different specification.

2. ***Cost/Friction Tool*** *(GRASS r.series tool)* – A cost or friction surface is obtained overlaying (a), (b), (c), (d) grids, propagating the minimum cell value.
3. ***Cumulative Cost Tool (****GRASS r.cost tool)* – Service Area – The cumulative cost/accessibility maps are produced selecting a central point, or points, and defining service areas.

Accessibility to major urban areas/regions (urban>1500 habitants/km^2, area>20km^2[9] is defined to 4 urban regions in Chad – N'Djaména, Moundou, Sarh, Abéché - calculated using roads layer (lines) intersection points with urban areas (polygons) for a total of 26 access points.

Assuming existing fish production/consumption deficit, external demand (exports, cross border trade, accessibility to large regional cities) was not considered.

4. ***Normalization*** – Units are normalized/scaled (0 to 100) for score calculations (weighted sum). Low accessibility (time or cost) 0, high accessibility 100.

[9] Area was lowered from previous analysis, adapted to the country's context.

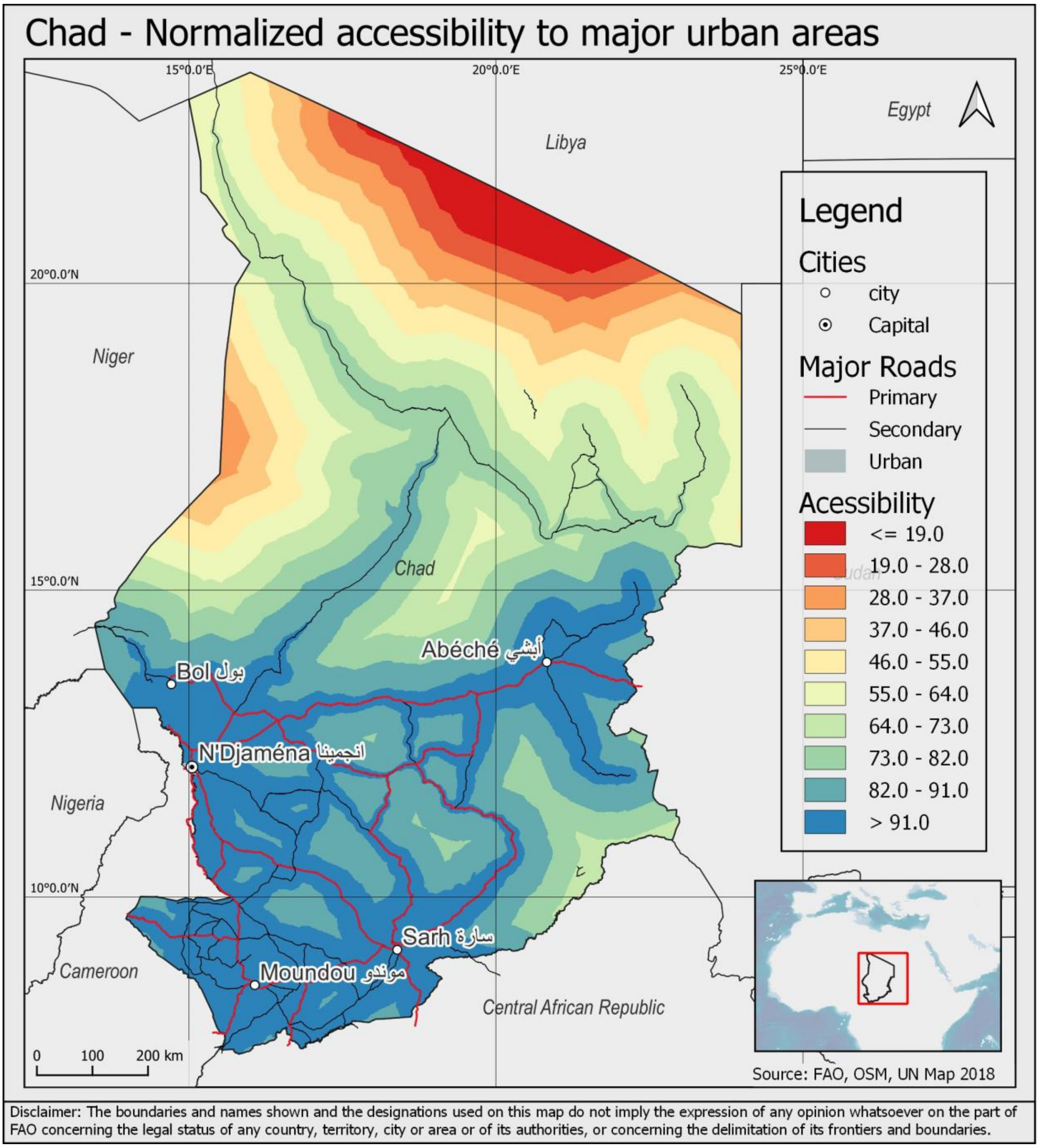


Figure 5 – Accessibility to urban areas map

4.2 SUB MODELS: MARKET/DEMAND

Market demand sub model utilizes population density and accessibility.

4.2.1 Cities/Urban areas

Large urban or metropolitan regions were defined as having more than 1500 habitants/km² and covering an area equal or larger than 20km². The following steps were applied:

1. ***Raster calculator tool: 1/0 layer where 1 = PopDens>1500***
2. ***Polygonise tool*** - converts the raster/grid cells to vector polygons.
3. ***Geometries (Check validity /fix geometries tools):*** Polygon geometries are checked for errors and validated.
4. ***Field calculator tool***: create a new field "Area" where *$area* (km²).
5. Export>save features as: UrbanAreas
6. ***Select by attributes***: * FROM UrbanAreas " WHERE "Area">20km².
7. Export>save selected features as: Major UrbanAreas.

4.2.2 Farmgate sales

Criteria sub-modelling applies Aguilar-Manjarrez and Narh classification to population density:

- Class 4 - Very suitable: 150-300 [h/km²]
- Class 3 – Moderately suitable: 25-149 [h/km²]
- Class 2 – Marginally suitable: 1-24 [h/km²]
- Class 1 – Unsuitable: <1 and >300 [h/km²]

Data is classified with the following sequence:

1. SAGA Raster tools – **reclassify** values: 1-4 pop density classes.
2. ***Normalization*** – Units are normalized/scaled (0 to 100) for location score calculations (weighted sum).

4.3 SUB MODELS: PHYSICAL GEOGRAPHY

4.3.1 Water

Availability is estimated using an annual water balance and Global Surface Water Explorer (GSW) seasonality and maximum extent data. GSW maximum seasonality value is used to evaluate the persistence of surface water for large water bodies for cage systems, the maximum extent (32-year time-series) is used as a flood area constraint for non-intensive pond systems.

Water balance sub-model uses WaPOR precipitation and evapotranspiration monthly time-series from 2009 to 2020, calculating a mean water balance layer, through the following steps:

1. ***Clipping*** to country borders.
2. ***GRASS r.series tool*** – mean value calculation.
3. ***Raster calculator tool***: modelling values: (Precipitation * 1.1) - (evapotranspiration * 1.3).
4. ***GRASS r.ressamp.stats*** - Resampling using aggregation (matching raster resolution).
5. ***Normalization – raster calculator*** – grid scaling normalizing (0-100)

Water requirement sub-model was adapted to Chad. Since large part of the territory is arid to hyperarid Sahelian and Saharan AEZ, the ***very suitable (>0mm)*** water requirement class areas is not considered.

Text Box 2.2 Water requirement submodel.

VALUE [mm]	INTERPRETATION	SCORE
> 0	Very suitable as a water source for ponds.	4
-2,000 to -1	Moderately suitable for ponds and costs for deeper ponds.	3
-2,000 to -3,500	Very likely to encounter water availability problems and construction costs for deeper ponds.	2
< -3500	Unsuitable many problems problems to fill ponds. High costs for constructing deeper ponds.	1

Figure 6 – Water requirement sub-model classes (Aguilar-Manjarrez & Narh, 1998)

The ***unsuitable*** areas are also excluded, modelling normalized 0-100 only the ***Moderately suitable*** and the ***Very likely to encounter problems*** classes.

Global Surface Water data processing

1. Extracted/downloaded in 3 tiles 10°x10° degrees for *max_extent* and *seasonality.*
2. ***Clipped*** to UN borders and ***merged mosaic*** to single dataset***.***
3. *Max_Extent* (flood areas mask layer)***: polygonise > dissolve***
4. *Seasonality:*
    - ***Raster calculator tool:*** *(“Seasonality”=12) * ”Seasonality”*
    - ***polygonise > dissolve***

4.3.2 Soil and terrain suitability for ponds

Soil suitability sub-model data is from Aguilar-Manjarrez and Narth study assuming there is no substantial change in conditions. Represents limitations for fishpond construction, uses FAO soil units, acid sulphate layer; organic layer; lime requirement; clay content; depth to water table; salinity/alkalinity; gypsum content; soil depths.

Slope is updated using higher resolution data (Watershed DEM 30s) and modelling steps are:

1. ***Clipping*** – Digital elevation model (DEM) and Soil data to country borders.
2. ***GDAL Slope tool****:* DEM to slope transformation (in degrees).
3. ***SAGA Raster tools – reclassify values*** – Slope layer classification (4 classes)
    - Class 4 - Very suitable: <2
    - Class 3 – Moderately suitable: 2 - 5
    - Class 2 – Marginally suitable: 5 - 8
    - Class 1 – Unsuitable: > 8
4. ***Raster Calculator tool***: Soil and terrain suitability for fishponds = (1.5X soils) + Slope
5. ***Normalization – raster calculator*** – grid scaling normalizing (0-100)

SoilSlope sub-model values are applied to modelling small scale extensive to semi-intensive integrated pond farming systems.

Intensive commercial closed systems modelling use slope data separately.

4.3.3 Potential Yield

Potential Yield sub-modelling uses data from Aguilar-Manjarrez and Narh study. Fish growth is directly proportional to the number of days within an optimal temperature range. Aguilar-Manjarrez and Narh originally estimated water temperature employing air temperature and wind velocity data for the considered species, and the fish yield estimation presented as crops/y. The potential yield layer is clipped for Chad and normalized/scaled (0, 100).

There are gaps in the fish yield datasets that might have impact on the final zoning exercise.

4.4 SUB-MODELS: INPUTS

4.4.1 Crops

Crop products and by products can be used directly as feed or as raw materials for feed mills. Local aquafeed production can be determinant for fish farming sustainability and competitiveness.

The crop input sub-model uses production aggregate from IFPRI MapSPAM 2017.

1. ***Clipping*** – To country borders.
2. ***Normalization – raster calculator*** – grid scaling normalizing (0-100)

4.4.2 Livestock

Livestock input can be considered for both organic fertilization (manuring) or the use by-products (blood, bones etc.) for feed ingredients. Different production systems requirements imply distinct sub-models.

Open non-intensive and integrated production systems

Sub-model uses chicken and duck density grids from GLW. Livestock is considered for manuring, feeding, and as natural aerators in the case of duck-fish integrated farming.

As feed, integrated systems benefit from chicken and duck nutritious rich faeces and poultry direct feed wasting. (Oribhabor & Ansa, 2006). As organic fertilizing (manuring) it contemplates that chicken are mostly farmed enclosed, employing cages and feeders, thus consisting of the best manure source.

Input sub-model uses GLW production spatial data:

1. ***Clipping*** –to country borders.
2. ***GRASS r.series tool*** – duck and chicken density aggregation (sum).
3. ***Normalization – raster calculator*** – grid scaling normalizing (0-100)

Intensive production systems

Most intensive production systems do not use organic fertilizing and are artificially fed, slaughterhouse waste by-products are low-cost alternatives ingredients for both industrial and small-scale feed mills.

Livestock is modelled aggregating Goat, Sheep, Pig, Cattle, animal density, weighted by the average live weight (LW), adopting Tacon 1989 and Vincke 1985 values, in (Aguilar-Manjarrez & Narh, 1998):

- Goat: 30kg
- Sheep: 30kg
- Cattle: 210kg
- Pig: 63kg
- Chicken: 2.2kg

Modelling steps:

- ***Clipping*** – individual livestock layers to country borders.
- **GRASS r.series tool –** animal density aggregation (weighted sum): (goat X 0.089) + (sheep X 0.089) + (cattle X 0.626) + (pig X 0.188) + (chicken X 0.007).
- ***Normalization – raster calculator*** – grid scaling normalizing (0-100)

5. SUITABILITY MODELLING

The zoning effort targets Catfish and Tilapia farming systems technologies differently affected in location by competing criteria or factors:

1. Extensive to semi-intensive open systems using ponds or small water bodies.
2. Peri-urban intensive/commercial catfish closed (semi-closed) systems using ponds, tanks, RAS, flow through or recirculation.
3. Intensive Tilapia farming systems using cages in large water bodies.

The following sections detail selected criteria, weighting, and applied constraints.

5.1 EXTENSIVE/SEMI-INTENSIVE SYSTEMS (CATFISH AND TILAPIA)

Extensive/semi-intensive and integrated small-scale farming systems, for both Catfish and Tilapia, are the most dependent on natural and geographic factors or criteria. Feeding can be based on natural food supply, from integrated systems (crop/livestock waste), or additional complementary feeding resourcing to on farm or locally produced feed.

Considered criteria:

a) Farm-gate sales.
b) Water Balance.
c) Soil/Slope - (1.5X soils) + Slope.
d) By-products inputs (Crops/Livestock) (1.5X ChickenDuck) + CropAgg).

Constraints (used as clipping mask layers):

a) Urban areas.
b) Protected areas.
c) Dams and Large Water Bodies.
d) Flood areas - GSW max extent (polygonise/dissolve raster).

5.1.1 Location Score

The location score consists of a simple arithmetic weighted sum of criteria normalized grids, theoretically varying from 0 to 100:

("WaterBalance" X 0.5) + ("Soil/Slope " X 0.25) + ("Byproducts" X 0.125) + ("FarmgateSales" X 0.125)

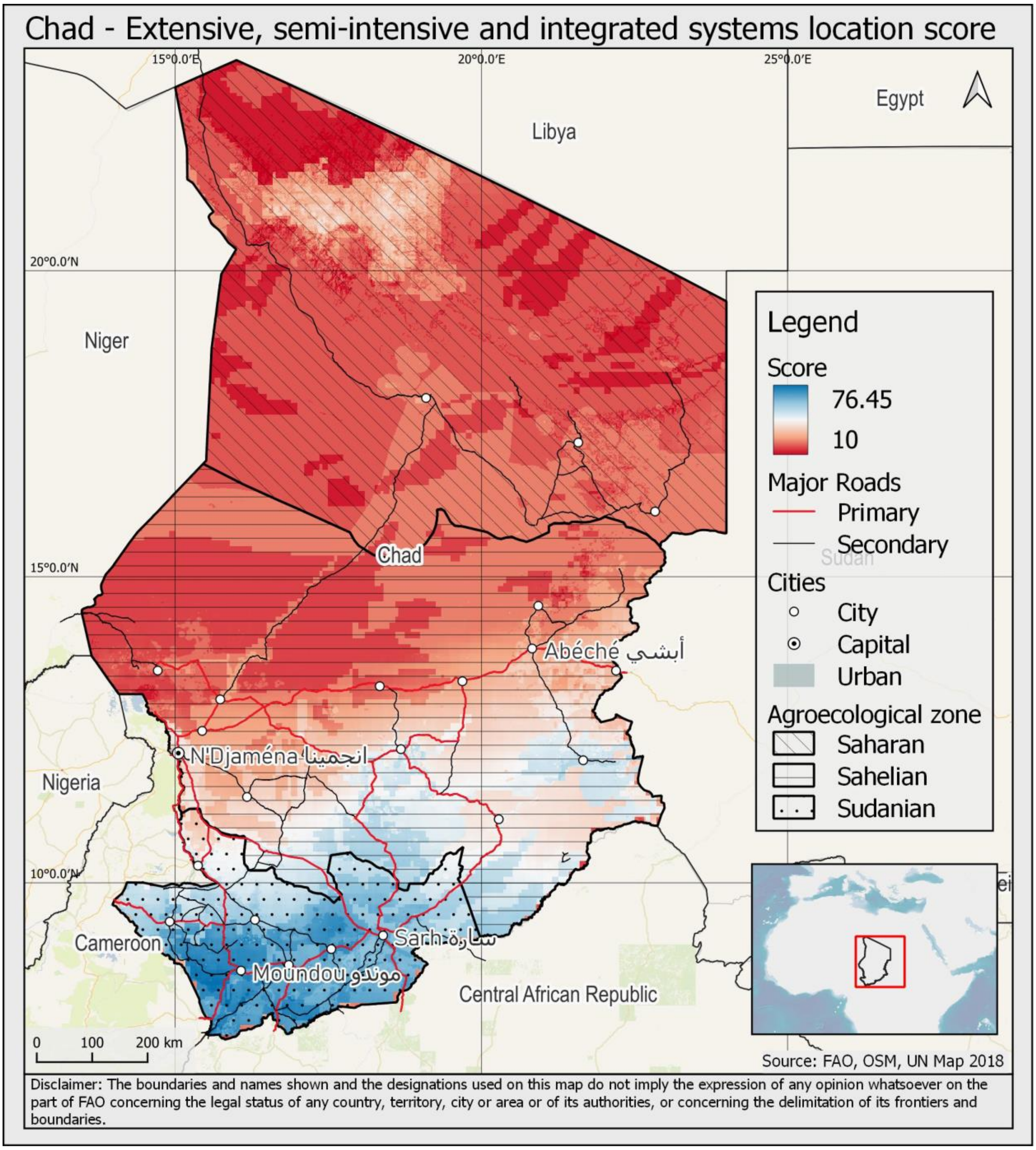


Figure 7 - Non-intensive and integrated systems suitability map

Unsurprisingly most suitable areas can be found in Chad's south Sudanian agroecological zone (Mayo-Kebi, Logone, Moyen-Chari, Tandjilé and Mandoul) regions, with some prominence to the east of the city of Moundou in the Logone and Mayo-kebi regions, lower location score suitable areas can also be found in the southern Sahelian zone in Guerá, Salamat and Sila regions. The northern two thirds of the country can be considered unsuitable.

5.1.2 Constraints and Final Mapping

The following constraints are applied:

a. Urban areas.
b. Protected areas.
c. Dams and Large Water Bodies.
d. Flood areas

Since the objective is to target food insecurity, improved nutrition and income diversification, the location score is also filtered using the asset wealth index (AWI) below the national average:

AWI filtering sub-modelling is obtained by - raster calculator: (‘AWI’<average) * ‘location score’.

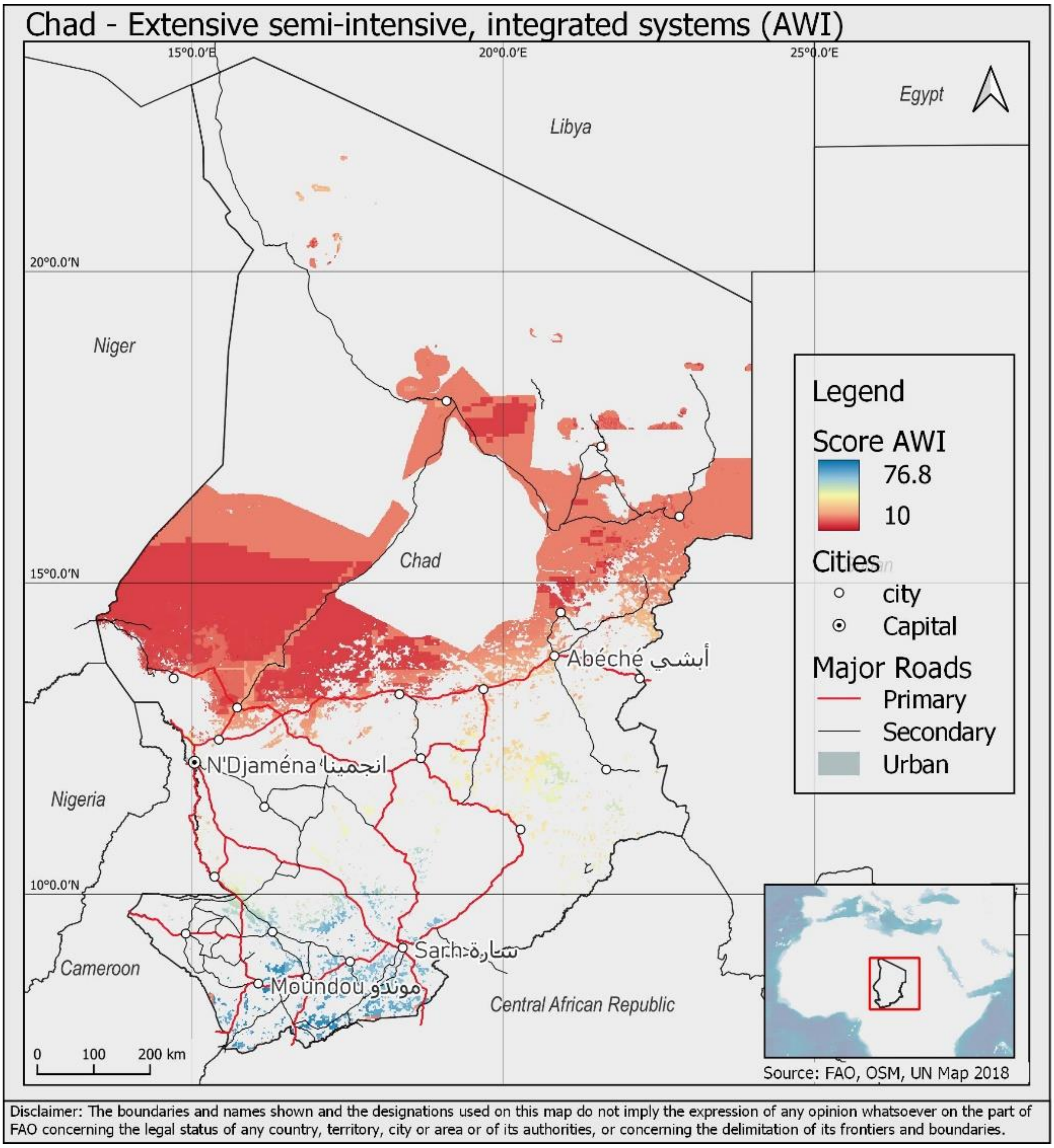
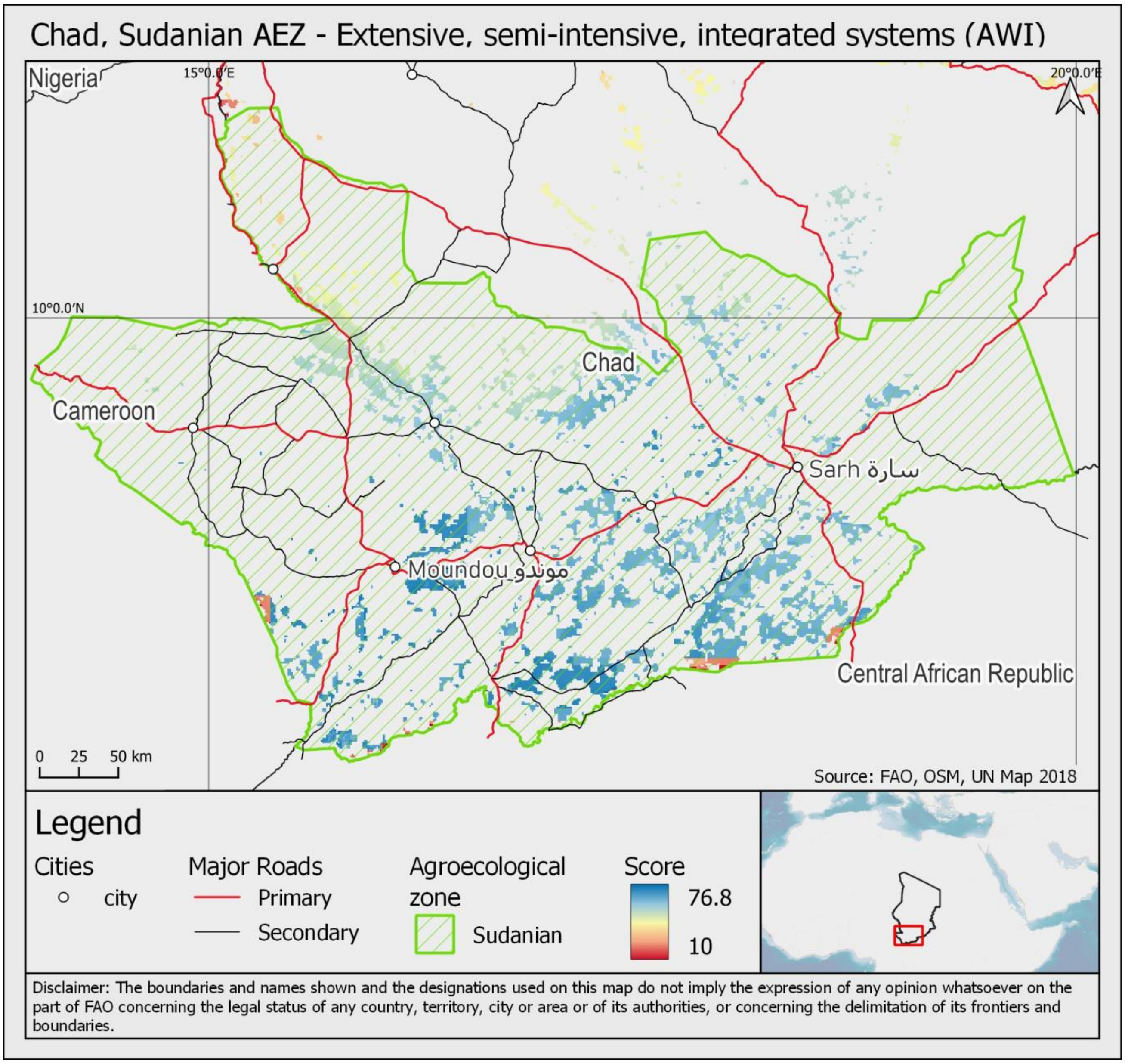


Figure 8 - Non-intensive systems (with poverty) map

Figure 8 allows the identification of the suitable areas where the AWI is below the national average. The lowest income suitable areas for extensive systems are also predominantly in the Sudanian zone south regions, with southern parts of Sahelian zone regions Guerá and Chari-Baguirmi also worth of further analysis.


Chad, Sudanian AEZ - Extensive, semi-intensive, integrated systems (AWI)
Nigeria
15°0.0′E
20°0.0′E
10°0.0′N
Chad
Cameroon
Sarh سارة
Moundou موندو
Central African Republic
0 25 50 km
Source: FAO, OSM, UN Map 2018
Legend
Cities
city
Major Roads
Primary
Secondary
Agroecological zone
Sudanian
Score
76.8
10
Disclaimer: The boundaries and names shown and the designations used on this map do not imply the expression of any opinion whatsoever on the part of FAO concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers and boundaries.

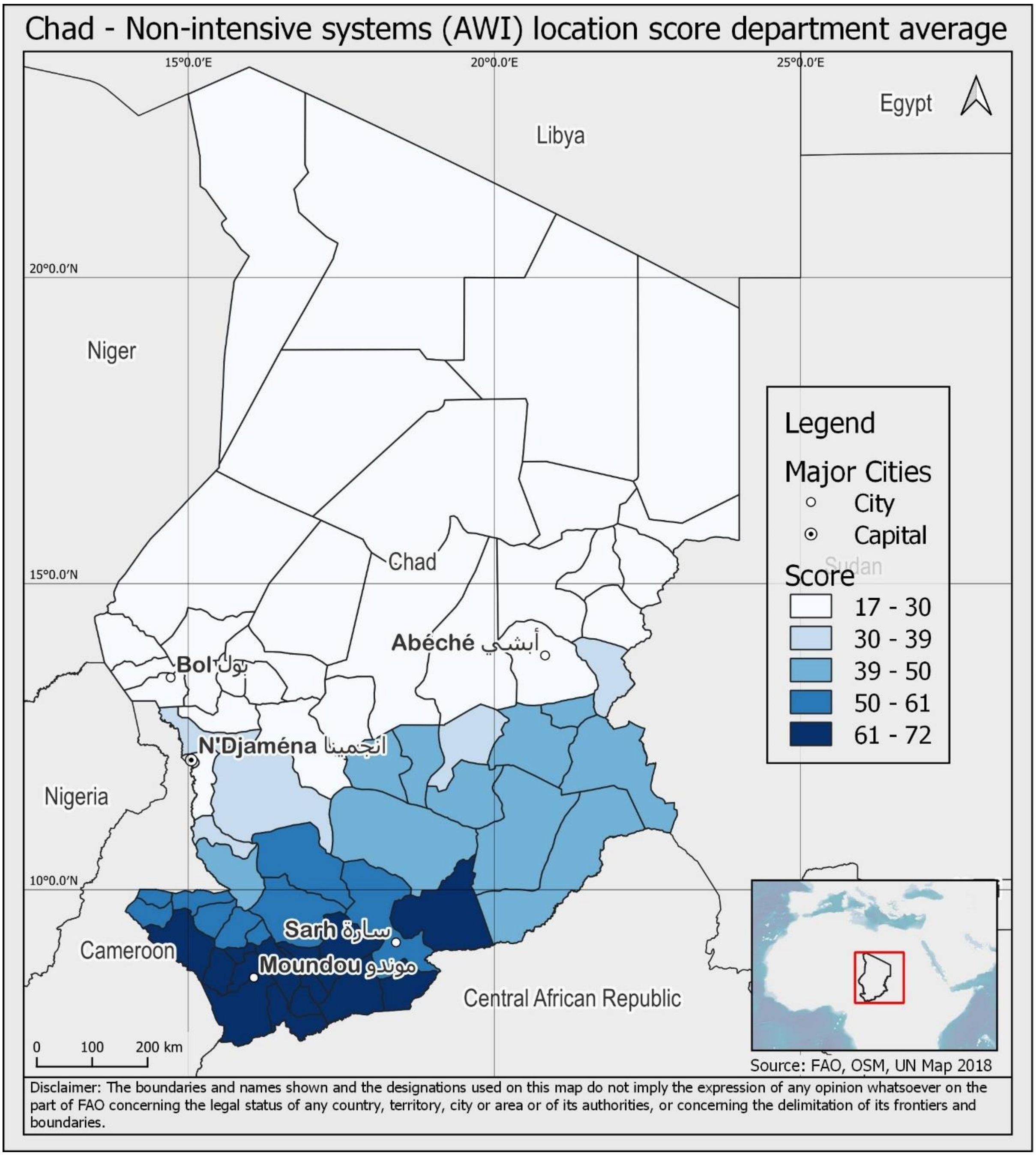


Figure 9 - "Department" average non-intensive systems location score map

Figure 9, the *department* average score supports the selection of administrative units for interventions. The southernmost regions Mayo Kebbi Ouest, Logone occidental/Oriental, Mandoul and part of Moyen-Chari districts are highlighted for interventions targeting improved nutrition and alternative income generation non-commercial systems. The top location score using the AWI below the average are:

- Lac Wey 71.5
- Guéni 69.9

- La Nya Pendé 69.6
- Kouh Ouest 69.2

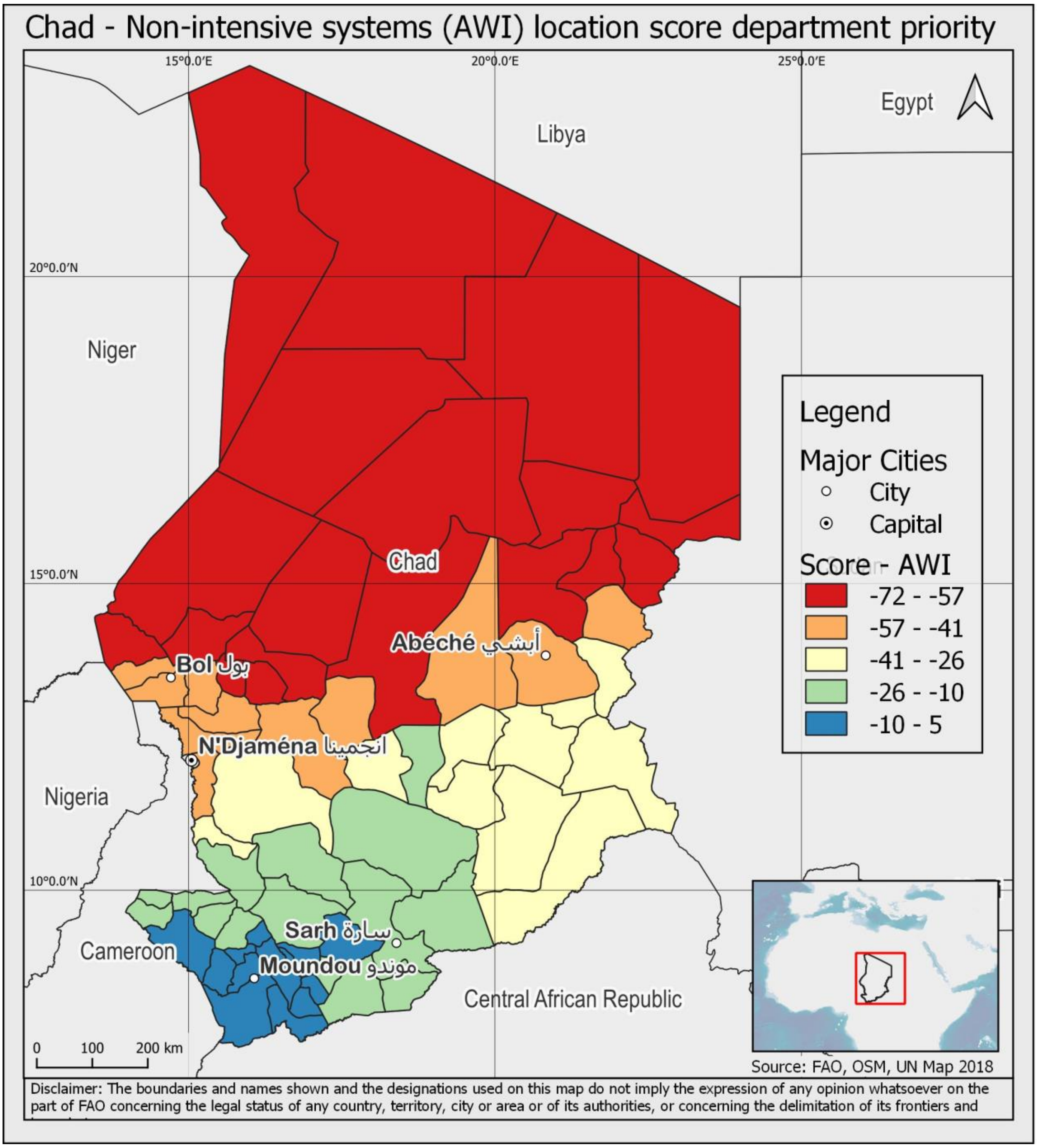


Figure 10 - "Départment" non-intensive integrated systems priority map

A *priority* index is defined by subtracting the normalized AWI to the location score, the highest its value (low AWI, high suitability) the highest the priority. *Figure 10* confirms the southern regions has having the highest priority, Logone Oriental and Occidental, The Mayo-kebi Ouest, but also parts of Tandjilé and districts of Mandoul. The city of Moundou appears very central to a general fish farming potential region, mostly in the Sudanian AEZ, with some of the Sahelian.

5.2 PERI-URBAN INTENSIVE CATFISH CLOSED (SEMI-CLOSED) SYSTEMS

Poor and unreliable energy distribution networks limit intensive closed farming systems (Satia, 2017) because there are operational needs [10] for systems pumps and aerators, to provide oxygen, to move water into and through the system, and to purify the water. There is a strong solar power potential in the entire country that can be used to overcome those limitations.

Modelling assumes that closed systems techniques using ponds, tanks, RAS, flow through and recirculation are less dependent on natural or physical geographical criteria:

- Require less water because are based in reuse/recirculation.
- Water balance can be even less significative considering that the modelling does not weight groundwater availability.
- Tank systems can be placed indoors or in compounds lowering climatic limitations.
- Land and soil requirements are minimal since tanks are produced with manmade materials - concrete, steel, fiberglass, or plastic.

Closed containment farming methods also pose smaller environmental risks due to controlled exchange between farm and environment. It reduces pollution, fish escapes, negative wildlife interactions, parasite, and disease transfer. In recirculation methods, water is treated and recirculated, with minimal wastewater discharges.[11]

Assumptions:

1. Closed intensive systems are not dependent on soil characteristics.

Considered criteria:

a. Market accessibility (major urban areas).
b. Water Balance (water requirements).
c. Potential Yield.
d. Crop input (CropAgg) - availability of agricultural by-products.
e. Livestock input (weighted animal density aggregation) - availability of livestock by-products.

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[10] https://thefishsite.com/articles/photovoltaic-applications-in-aquaculture-a-primer

[11] https://www.seachoice.org/info-centre/aquaculture/aquaculture-methods/

f. Slope - terrain suitability.

Constraints:

a. Urban areas.
b. Protected areas.
c. Dams and Large Water Bodies.
d. Flood areas

Final maps exclusive criteria:

a. Mobile broadband coverage.
b. Maximum distance to major roads.
c. Maximum distance to bank agency.

5.2.1 Location score

The location score consists of a simple arithmetic weighted sum of normalized grids, theoretically varying from 0 to 100, with the following weighting:

(“Accessibility MajorUrbanAreas” X 0.4) + ("WaterBalance" X 0.25) + ("potential Yield" X 0.15) + (“CropsInput” X 0.075) + (“LivestockInput” X 0.075) + ("Slope " X 0.05)

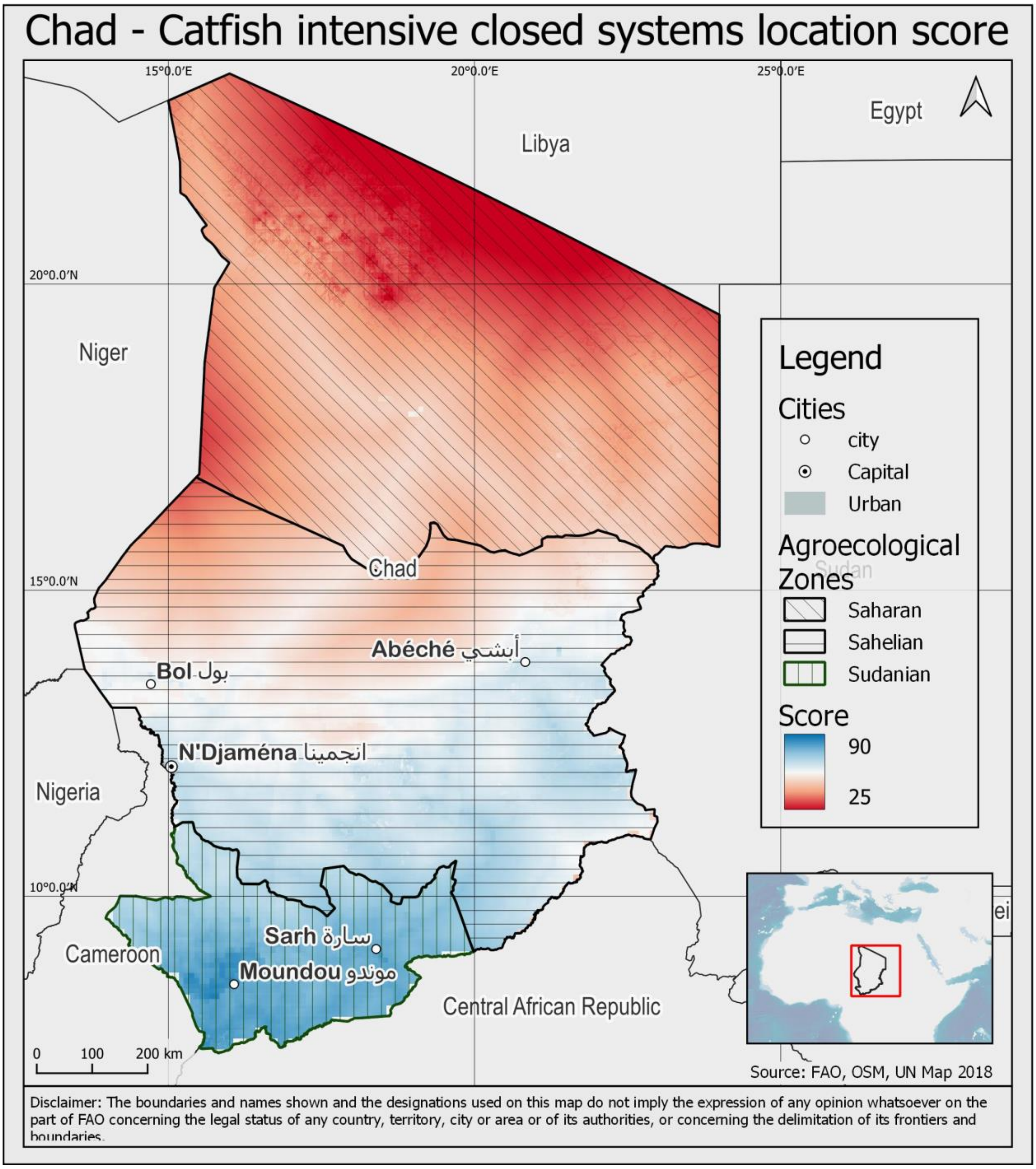

Figure 11 - Intensive closed catfish systems location score map

The urban market accessibility (demand) criterion is most weighted for the intensive commercial closed catfish systems, the spatial pattern follows output markets, urban areas, but also resource limitation. Southern Sudanian AEZ with highlight to Moundou area, and south part of the Sahelian AEZ appear as most suitable.

It must be referenced that accessibility to urban areas in considered to cities with a population density above 1,500 habitants and more than 20 square kilometres: N'Djaména, Abéche, Moundou and Sarh, not weighting the total population size doesn't give the capital a score according to the market size dimension.

5.2.2 Final Maps

Final maps identify zones suitable for investment, employing as final or exclusive criteria: distance to major roads, access to ITC (mobile broadband coverage), and physical access (distance) to finance.

ITC usage has a growing importance in marketing, helping to reduce information asymmetry between traders and producers, but also allows improved extension services, microcredit apps/tools, or innovative digital finance using, for example, blockchain technologies. Innovative applications can also be envisioned in fields like disease monitoring or management.

Final mapping defines access to finance by a linear distance to/from a bank agency.

Final mapping follows the aproach:

- ***Buffering*** – A buffer area for all the features in an input layer using fixed or dynamic distance:
    - Major roads - 2km (0.018 degree) buffer radius.
    - Bank agency – 20km (0.18 degree) buffer radius.
- ***Intersection*** - extracts the overlapping portions of features in the Input and Overlay layers: *Roads_Buffer, Bank_Buffer* and *Mobile_Broadband_coverage*.
- ***Dissolve*** - Takes the intersection vector layer and combines the features into a new feature, a single polygon.
- ***Clip Raster by Mask Layer*** – The grids are extracted using the polygon.
- ***Raster Calculator:***
    - Final recommended top score sites are selected using the 90th or the 95th percentile and raster calculator: *"raster">95th percentile X "raster"*
    - Setting the value 0 as no data: (("raster" >0) X "raster")/ ((("raster" >0) X 1) + ("raster" >0) X 0)))

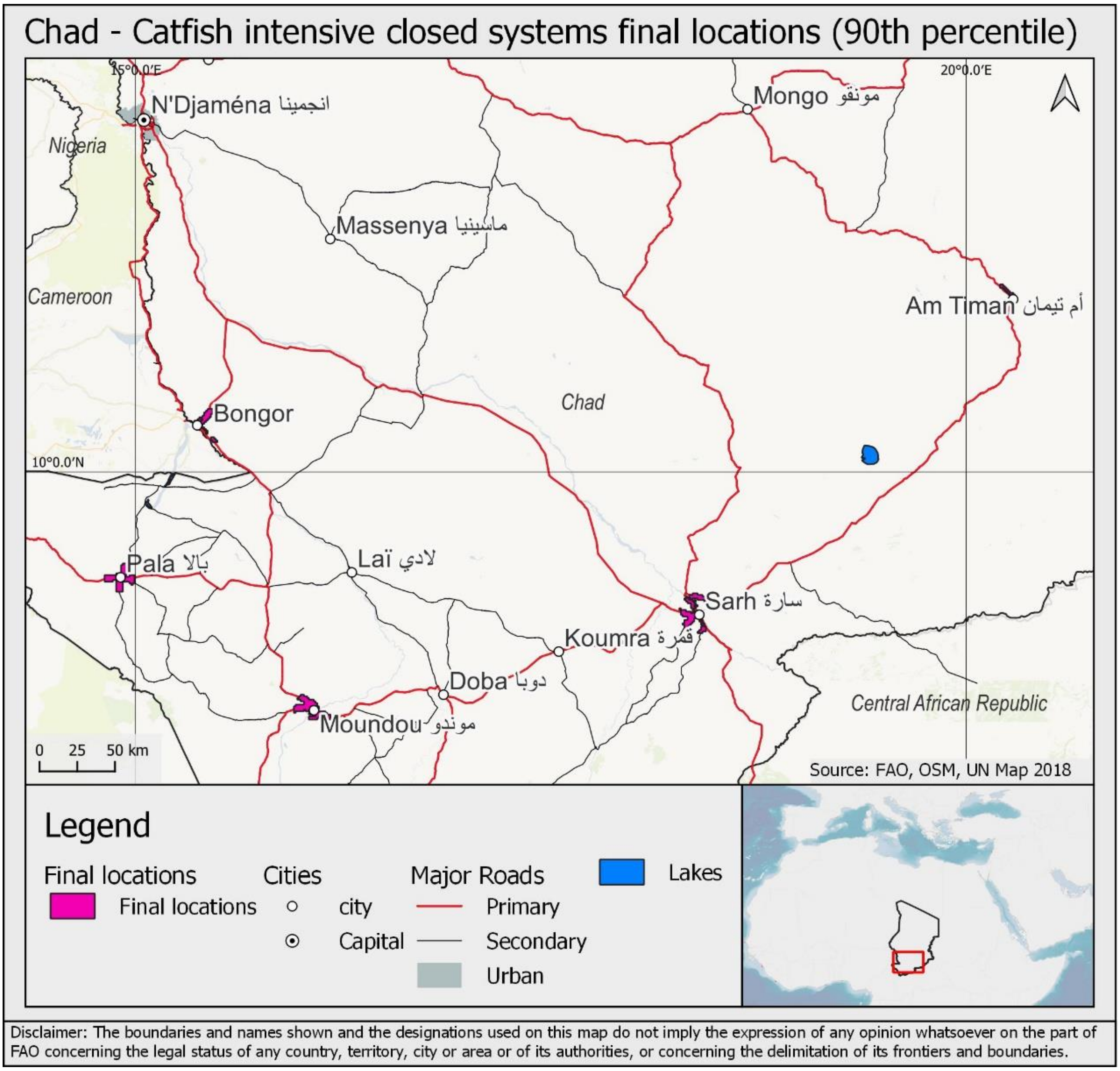

Figure 12 - Intensive closed systems suitability map – 90th percentile

Intensive catfish closed system's final location mapping point to southern urban centres, Bongor, Pala, Moundou and Sahr, and a smaller area in Am Timan. Interpretation must consider data flaws, finance access is used as final exclusive criterion and available data for bank agencies might not be exhaustive, complete. Another concern is the accessibility modelling approach, with urban areas N'Djaména, Abéche, Moundou and Sarh, weighting the same.

5.3 OPEN INTENSIVE SYSTEMS - TILAPIA IN LWB

Intensive tilapia farming using cages in LWB are one of the most profitable fish farming systems. They require low initial investment, are usually located in public waters, and have low construction and energetic requirements. Additionally, the tilapia breeding cycle is interrupted in cages, simplifying seeding management, and augmenting productivity, and harvesting also comes at low cost.

The disadvantages of open aquaculture systems result from exchanges with surrounding environment, transferring waste, chemicals, parasites, and disease, and with a much higher potential for fish escape. These systems are more vulnerable to predation and poaching, and farming in public waters face competing interests and its legal status might not be well defined. Not all LWB offer appropriate conditions.

Tilapia post-harvest value chain is more demanding compared with the, mostly marketed alive, resistant catfish. Incipient infrastructure deployment - rural electrification, alternative energy sources and road infrastructure – limits large scale distribution requiring cold chain/storage.

Chad LWB dataset layer was modelled using the Global Surface Water (GSW) seasonality layer where seasonality is 12 months (maximum).

The modelling methodology defining location factor is the presence of permanent water.

Criteria (score):

a. Market accessibility (large urban areas).
b. Crop input (CropAggGAEZ) availability of agricultural by-products.
c. Livestock input (weighted animal density aggregation) availability of livestock byproducts.
d. Tilapia potential yield.

Constraints:

a. Protected areas.

5.3.1 Location Score

The location score consists of a simple arithmetic weighted sum of normalized grids. Varying from 0 to 100, with the following weighting:

(“Accessibility MajorUrbanAreas” X 0.40) + (“CropsInput” X 0.2) + (“LivestockInput” X 0.2) + + (Tilapia Yield x 0.2)

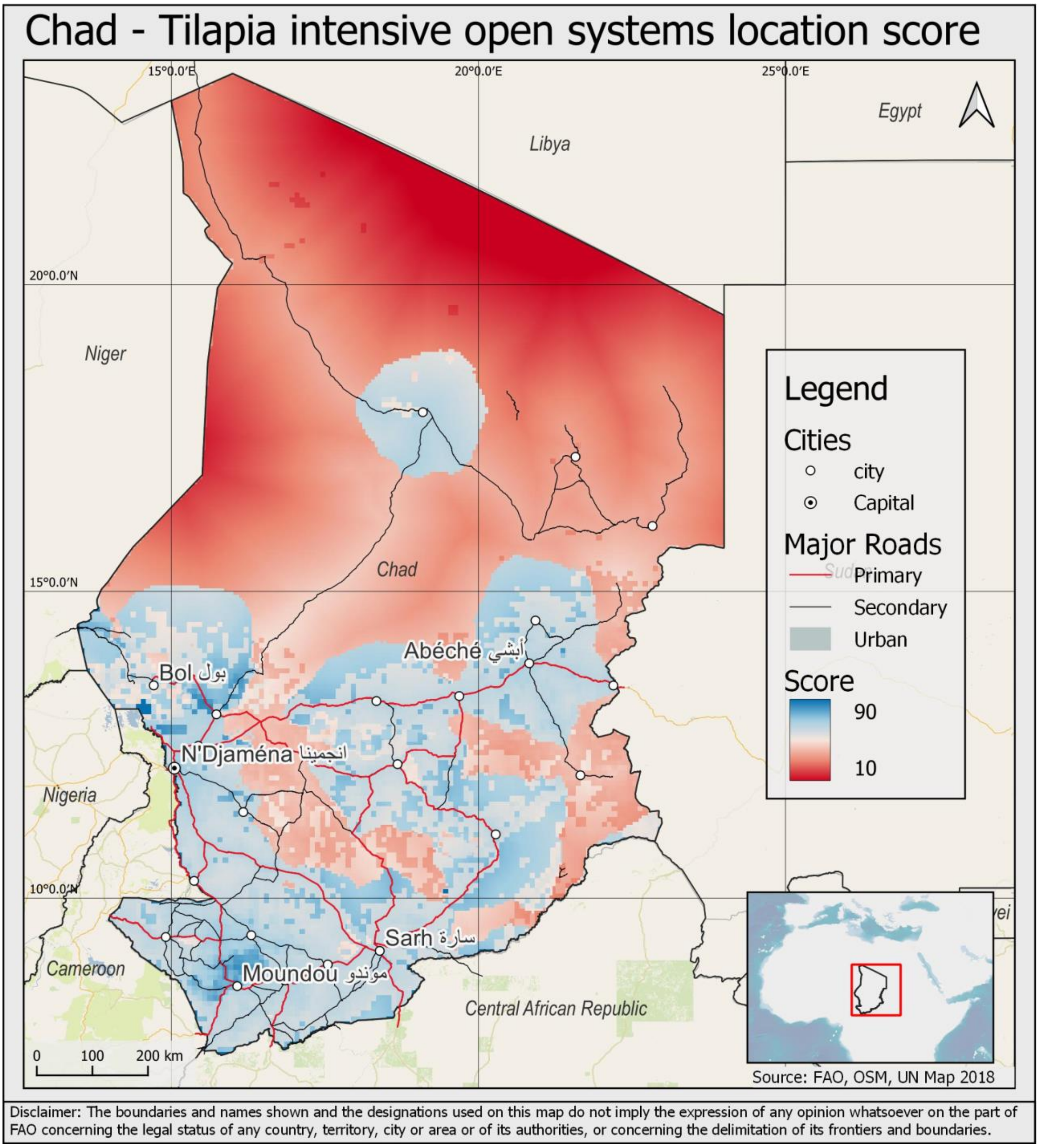

Figure 13 - Tilapia suitability score map

High location score areas are North of N'Djaména, Moundou, and in small areas in the border with Cameroun and the Central African Republic

5.3.2 Constraints and Final Mapping

Recommended locations require the presence of permanent water, final mapping follows the approach:

1. Definition of a 1km **buffer from permanent water** GSW (seasonality = 12)
2. ***Zonal statistics*** extraction of the maximum (max) score value from the location score raster to the permanent water buffer layer polygons.
3. ***Permanent water buffer symbology*** - Classified, with display of the top class (80^{th} percentile).

Large scale mapping is done for 5 regions displayng the greatest potential for Tilapia cage systems.

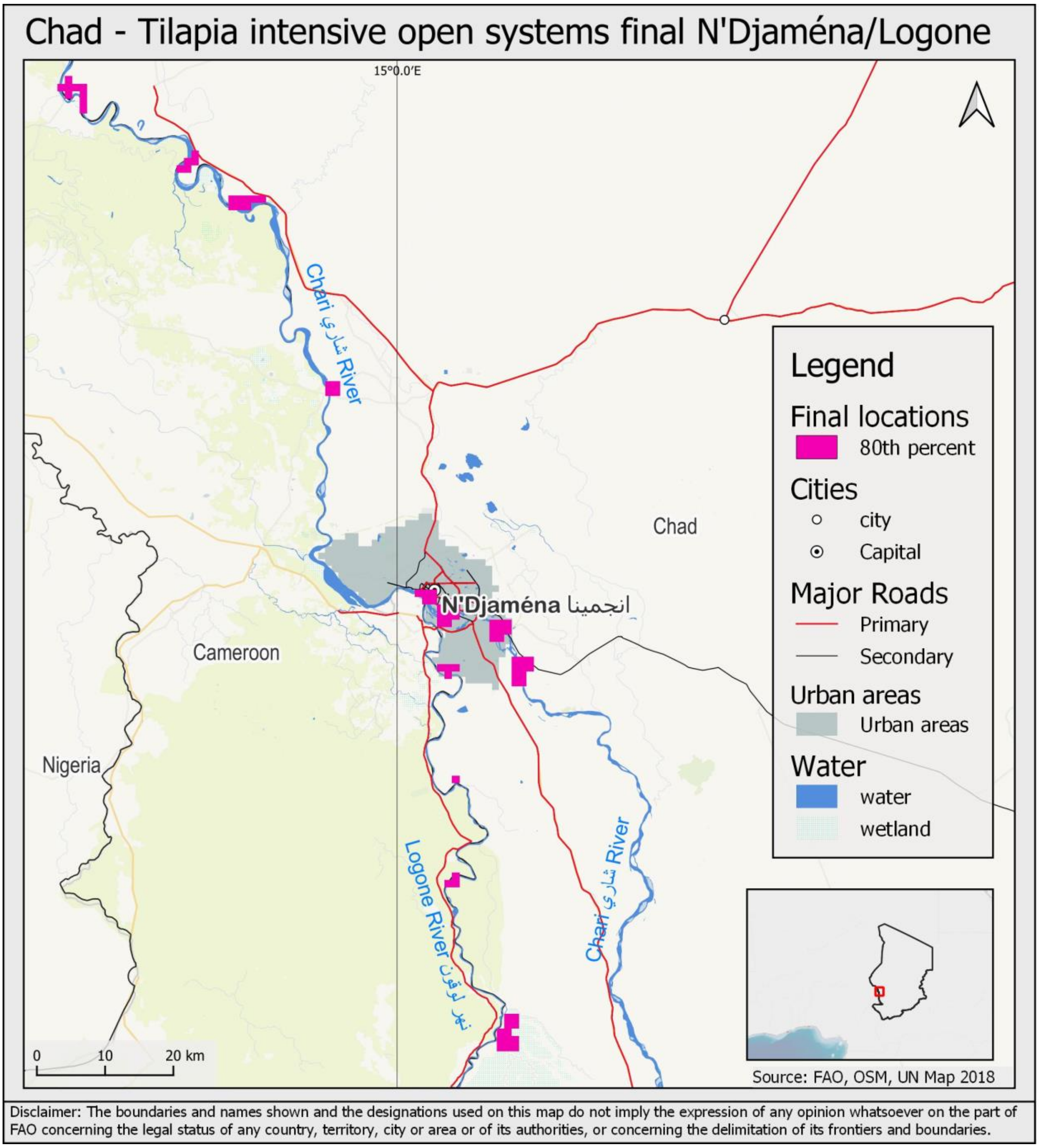

Figure 14– N'Djaména - potential large water bodies for intensive tilapia farming map (cage/nets)

N'Djaména and the Chari and Logone river bordering Cameroun appear to have potential zones requiring further inquiry.

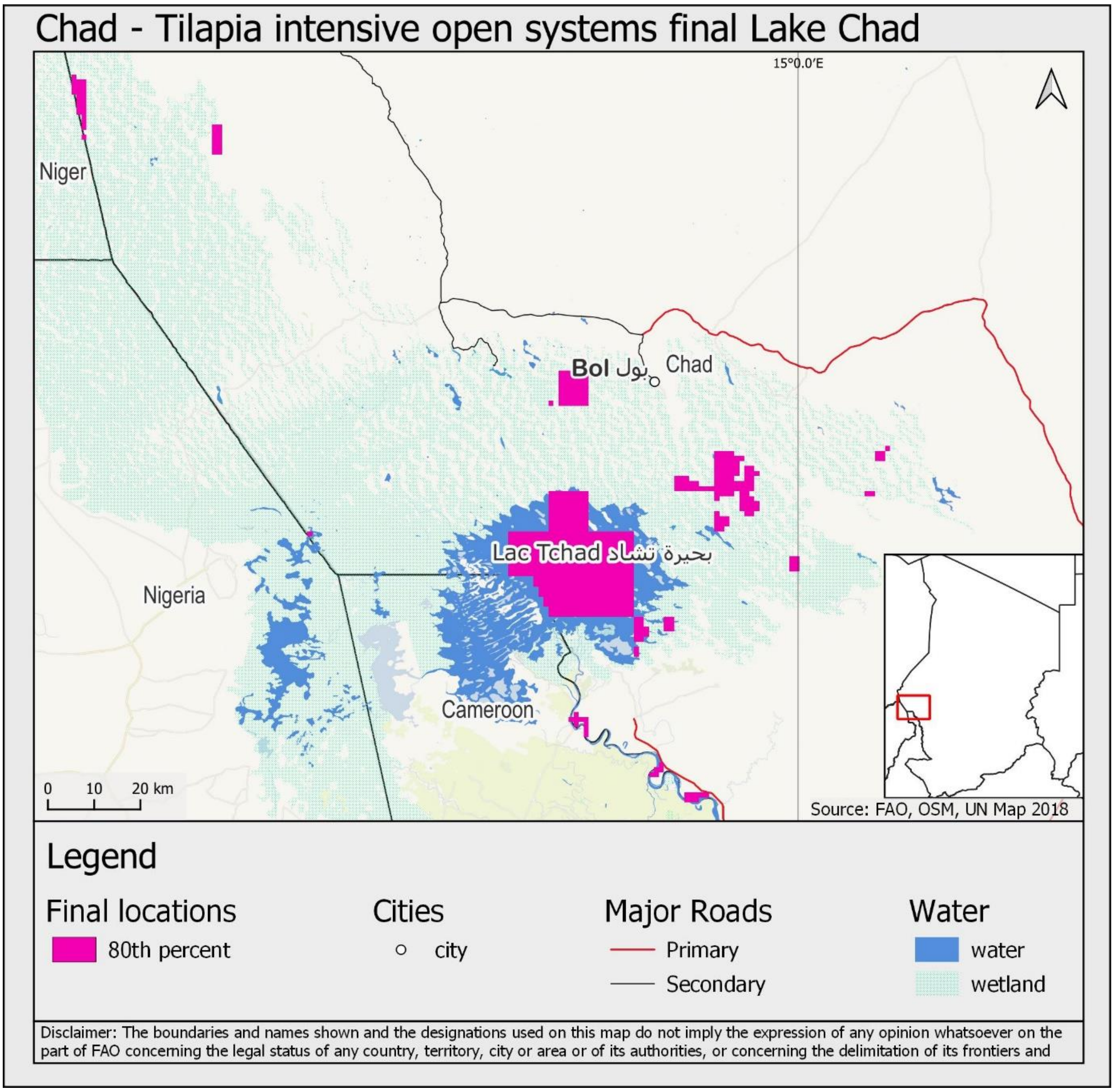

Figure 15 – Lake Chad - potential large water bodies for intensive tilapia farming map (cage/nets)

Lake Chad region water, wetlands, and Chari River expected potential is confirmed by the analysis.

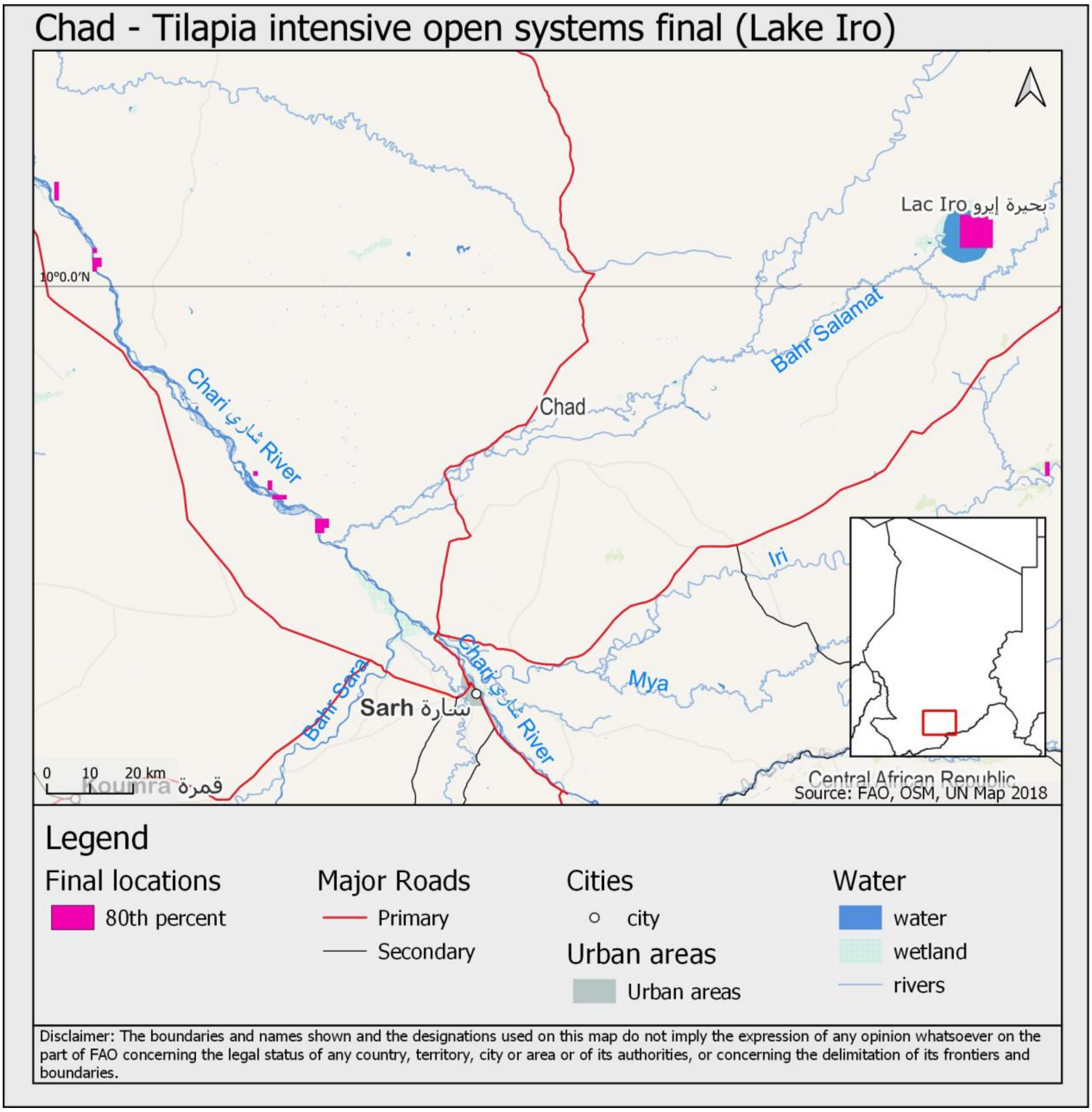

Figure 16 – Lake Iro - potential large water bodies for intensive tilapia farming map (cage/nets)

Small areas in the Chari River northwest of Sahr and Lake Iro show a high location score.

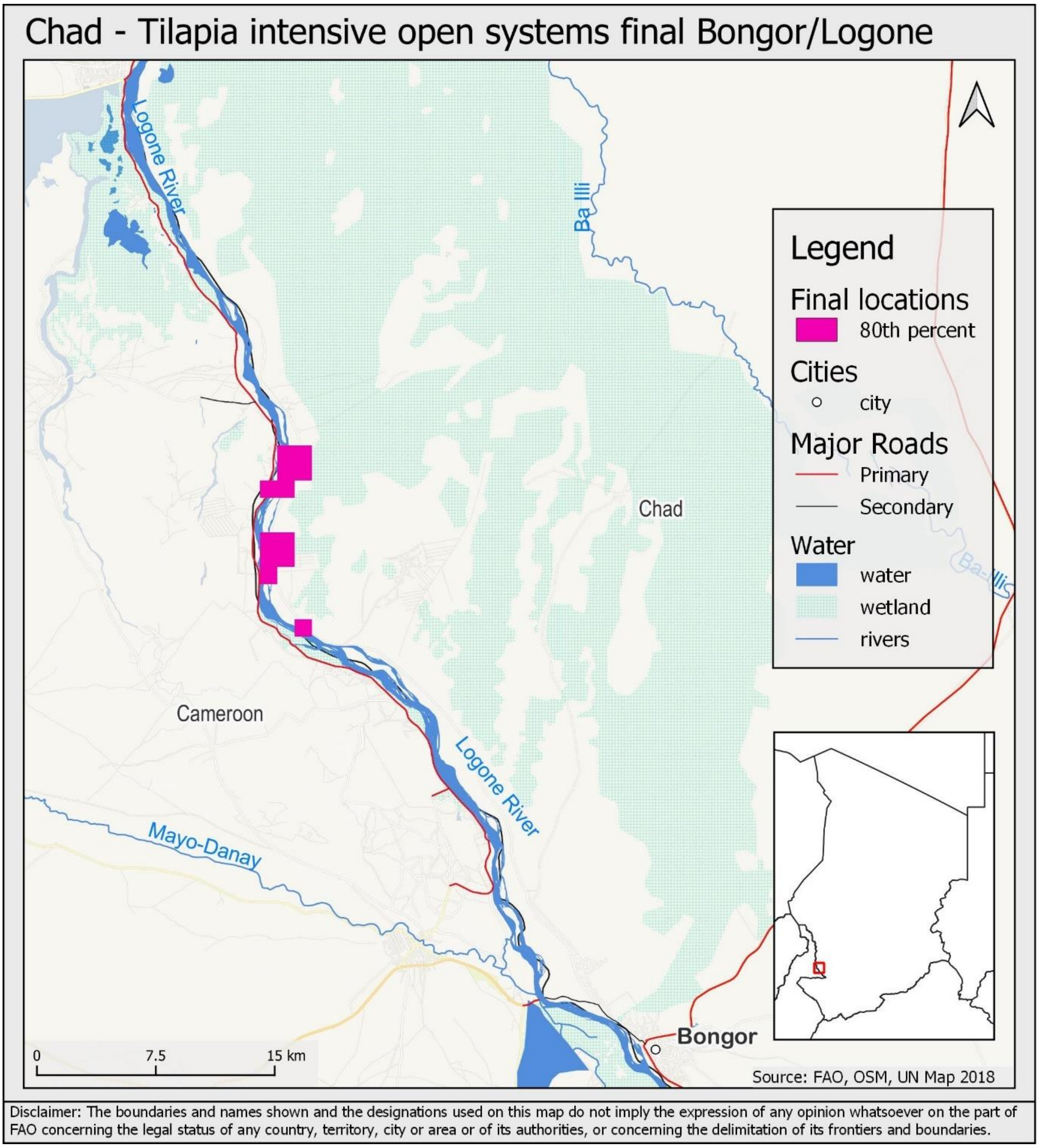

Figure 17 – Bongor - potential large water bodies for intensive tilapia farming map (cage/nets)

In the northwest of the city of Bongor and the Maga reservoir, the Logone River also appear to provide suitable conditions.

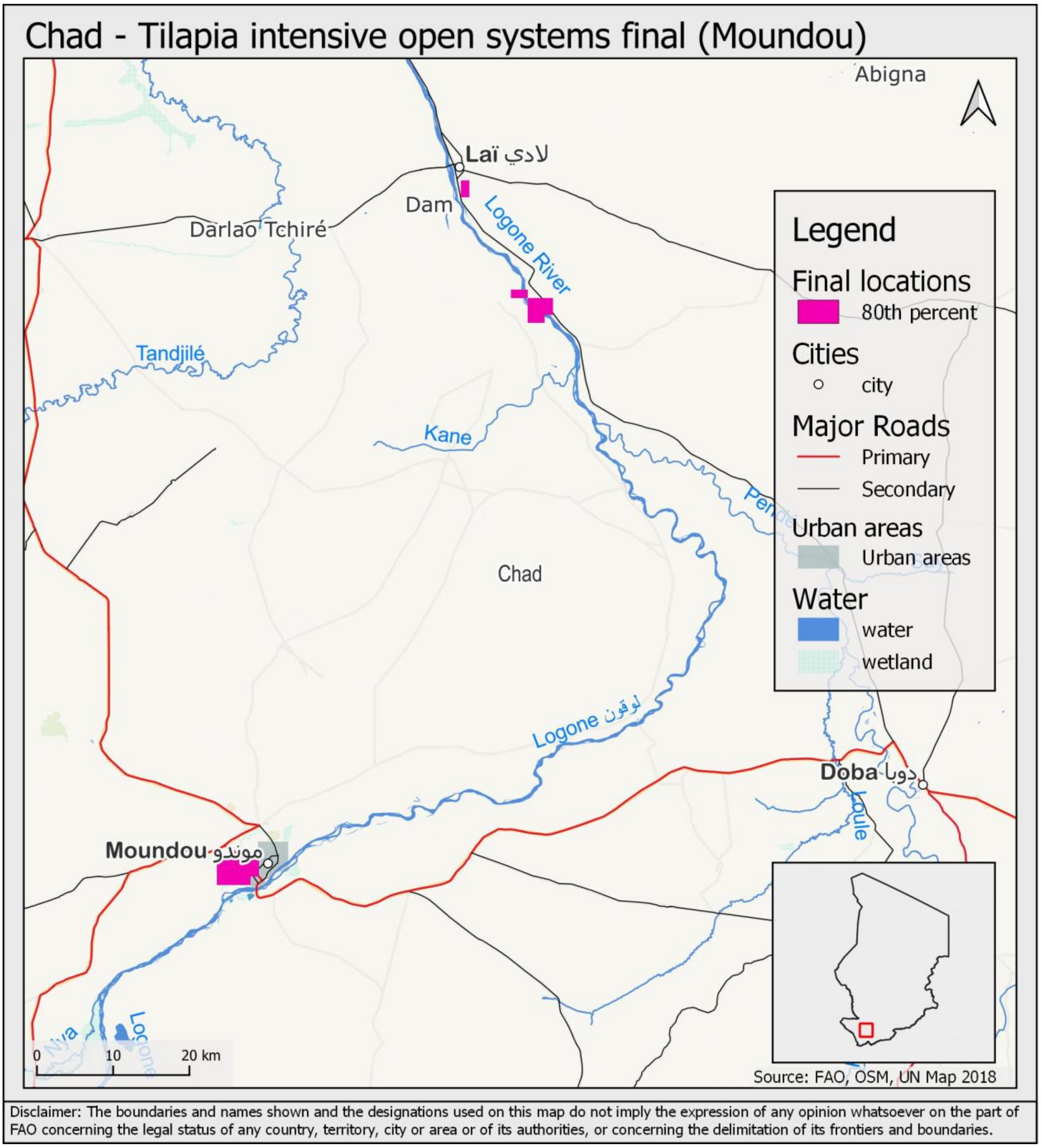

Figure 18 – Moundou - potential large water bodies for intensive tilapia farming map (cage/nets)

The Wey Lake in Moundou and Logone River in the south of Lai.

CONCLUSIONS

This section includes conclusions, closing remarks on modelling assumptions and results.

Chad is one of the worlds most landlocked countries and around half of the country is in the desert arid climate of the Saharan AEZ. During the Holocene between 12,000 and 5,000 years ago, the region was characterized by a green landscape, with pastures and trees, numerous lakes, and large river networks, with the Mega Lake Chad being around twenty-five times larger than today, more than 350,000 km2. Fishing is practiced in the Sahelian and Sudanian agroecological zones lakes, wetlands, and river floodplains, with the major fishing area in the Lake Chad and major tributary the Logone/Chari River system, but also taking place in smaller lakes like the Fitri, the Iro and the Léré.

Fisheries capture production is stable around the 100 thousand tonnes for the last decade, with variations reflecting precipitation irregularity impacting lake, wetlands and flood-plains area and fish availability. There is a clear fish production consumption gap, the country is a net importer of fish and fishery products, and aquaculture production is still extremely limited (430 tonnes in 2017).

Targeting the development of a modern commercial private fish farming sector, in 2010 the national government outlined a Strategic Framework for Aquaculture Development under the scope of which developed a National Aquaculture Development Plan (FAO, 2012). The plan defines areas with high potential and specific objectives like the development of extension services and training, fish farming systems demonstration, the creation of conducive institutional and economic environment, including the country's niche production of spirulina (dihé).

Fish farming has a reasonable growth potential in the southern Sudanian AEZ, but water scarcity and irregular precipitation sets direct and indirect constraints to its development. Cage systems in waterbodies particularly face a complex set of biophysical, social, political, governance, security challenges.

LAKES, WETLANDS AND WATER CONFLICTS IN THE SAHELIAN AGROECOLOGICAL ZONE

Extreme droughts in the 1970s and 80s increased the lakes economic relevance, where production systems are characterized by a mobility of activities and labour, defined by the pace and level of seasonal floods. Large scale irrigation developments also impacted the mobility, the multi-activity, and the multi-functionality of space, and consequently the resilience of socio-ecosystems.

After that period, while a wetter phase set the recovery of the lakes area, migrations further disturbed socio-ecosystems and customary, traditional, territorial governance, where natural resources regulation and access centre on precipitation irregularity and the interconnectivity of activities.

Fisherfolk migrations and newly introduced techniques furthered land, pond and water appropriation and at the same time that State means to enforce rules and compliance are limited, overlapping with customary authority regulation, and creating parallel taxations by local state and military actors (Kiari Fougou & Lemoalle, 2019).

Since 2009 violence and military repression further stuck development and relations between societies and environment causing population displacement, disappearance of economic outlets and changes in herd routes.

While in some areas, governance of natural resources based on coordination between users and absence of exclusion, enabled a territorial development centred on multi-use of space, demographic densification, and economic intensification (Rangé, 2019). From the mid-2000s, technical change, pastoral pressure, farming densification, and political instrumentalization of land further catalysed conflict.

In Lake Fitri, resources and traditional Bilala Sultanate customary governance also came under pressure from demographic, social, economic, and political change: transhumant herders, migrant fisherfolks, improved accessibility to urban markets, environmental and fisheries regulation.

Demographic pressure from population growth and migration, diversity of resources and seasonal fluctuations, plurality of actors and complexity of rights of exploitation are competing reasons explaining a high conflict potential, setting major constraints to economic development in general and fish farming since water is central to disputes. Challenges are common and persistent to the Sahel's exposed continental waters dependent on climate change, and the complex systems that govern links between nature and society in variable environments, in an overall context marked by rising insecurities. (Raimond, 2019)

Development projects and fish farming policies must so reflect on a series of conditions that can be found in different scale through all the Sahel:

- The State owns the land, but land tenure traditional systems are based on customary lineage property management. Potential is defined by flood levels, access governed by traditional rules, and commons are guaranteed by a founding ancestor without exclusive property rights. Property is collective at family level; individuals benefit from usufruct.
- There is great ethnic diversity, in Lake Chad the most important groups are the *Boudouma*, the *Kanouri*, the *Toubou*, the *Fulani* and the *Arabs* (the *Boudouma* are lake Chad autochthones and control most fishery's resources).
- Access and control of resources increased tensions between groups, reviving conflicts, e.g., the *Fulani* and *Boudouma*.
- In lake Chad basin regional settlements were disrupted by the insurrection and repression causing around 2 million refugees.
- Economic agreements separated and parcelled vast areas to private development projects (Iocchi, 2020).
- Groups face increasingly problematic transnational mobility.

The return to "abandoned" areas and regulation between former rights holders and new occupants is highly problematic (Magrin & Lemoalle, 2019). Emergency and forced evacuation opened prospects for opportunist actors' occupation, while State and large international players also set for large-scale land acquisitions. The intensification of resource competition seriously questions dispute-settlement practices and community-level authorities, now unable to respond to the advance of a wide range of interests by powerful actors.

TILAPIA CAGE SYSTEMS

There are a set of general disadvantages to Tilapia cage systems like losses to poaching, damage from predators or weather events, lesser tolerance of fish to poor water quality, dependence on fish-feed, exchanges with surrounding environment and increased risk of disease and parasites.

But adding to that, Chad's endorheic, eutrophic, shallow lakes, present further specific challenges. Organic waste dilution and flushing limitations can lead to low water quality and accelerate eutrophication (Garcia et al., 2014), and there is evidence of organic pollution from domestic waste and animal manure which influence water quality (Mikail et al., 2018). In Lake Fitri there is evidence of exceeding heavy metals parameters, above acceptable limits according to international standards, but also pesticides, on both fish and water (Oumar et al., 2018).

Shallow lakes are challenging to cage farming, as a rule, cage floor should be a minimum of three feet above the bottom to avoid waste accumulation and low oxygen levels, but greater depths promote rapid growth and reduce the possibility of parasitism and disease. Also, currents replenish dissolved oxygen and remove metabolic wastes, cages need water circulation and avoiding weed beds and shallow waters[12].

Cage culture in waterbodies commonly faces competing interests and complex legal status, even more in the case in sub-Saharan Africa and in the Sahel, where characteristic land tenure systems, central state management overlapping with traditional customary governance, and conflicts over resources are rule, clearly adding to that complexity.

MODELLING APPROACH

Departure research questions are:

1. *What are the regions and states where fish farming should be promoted for poverty alleviation, improving nutrition, and food security?*
2. *Where are the best sites for intensive commercial closed farming system investment?*
3. *Where are the best sites for intensive commercial Tilapia fish farming open systems?*

Research methodology followed previous Geographic Information Systems (GIS) fish farming suitability assessment analysis. A brief literature review on aquaculture fish-farming sector context, background, and perspectives. A GIS Multi-Criteria Decision Analysis (GIS-MCDA) modelling applying weighted factors, constraints, and exclusive criteria.

Fish farming suitability/potential zoning develops from Aguilar-Manjarrez and Nath study on warm and temperate freshwater fish farming suitability in continental Africa, raster-based GIS-MCDA using fish-farm and land-quality factors, with sub-models and categories of criteria:

1. Constraints (urban areas, large water bodies, protected areas).
2. Water requirement.
3. Soil and terrain suitability.
4. Inputs – crops and livestock.

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[12] https://thefishsite.com/articles/cage-culture-of-tilapia, https://www.globalseafood.org/advocate/lake-reservoir-characteristics-affect-cage-culture-potential/

5. Farm-gate sales - as a measure of population density classification.
6. Potential yields.
7. Urban market size and proximity.

Sector growth, fish farming systems, and data availability, all evolved since late 20th century, thus imposing updating and reassessment of data, criteria, weighting, and constraints.

Two distinct zoning efforts were defined:

1. To ***define and suggest regions and departments where investment can positively impact poverty, hunger, malnutrition, and food security*** - Extensive to semi-intensive small-scale integrated farming systems.
2. ***To select the best possible sites (high return on investment) for intensive commercial systems***, for both:
    a. Catfish closed intensive farming systems using re-circulating tanks, raceways flow-through systems, and ponds.
    b. Tilapia open intensive farming systems in large water bodies (LWB).

Distinct **farming systems models** are developed based on specific theory defining criteria combinations, weighting, and applying separate constraints:

1. Open non-intensive and integrated fish/crop farming systems – using ponds or small waterbodies.
2. Catfish closed Intensive systems –closed/semi-closed-circulation technologies: recirculating tanks, raceways, flow-through systems, and ponds.
3. Tilapia open intensive systems in LWB – using open-net pens/ cage techniques in public waters.

Modelling criteria cover: physical geography conditions, supply, demand, infrastructure, and accessibility:

1. Physical geography conditions:
    a. Water requirement.
    b. Soil.
    c. Terrain suitability (slope).
    d. Potential yield (temperature).
2. Supply

a. Crop production– feed.
b. Livestock – animal density – feed and organic fertilizing.

3. *Demand* - Human population density – farmgate sales and markets (urban/metropolitan areas).
4. *Infrastructure* - Transportation network (accessibility ports and urban/metropolitan areas).

Infrastructure and demand (market) sub-models involve raster-based travel time/cost analysis and is processed for large urban areas.

Applied **constraints** (according to farming system specificities):

1. Urban Areas.
2. Protected Areas.
3. Large water bodies.
4. Flood areas.

Final mapping **exclusive criteria** for intensive closed systems:

1. Distance to major roads.
2. Access to IT - mobile broadband coverage.
3. Access to Finance

CLOSING REMARKS

Closing remarks discuss assumptions and pitfalls, findings limitations, and future developments.

The exercise focuses on warm-temperate freshwater fish farming suitability modelling for African Catfish and Nile Tilapia species.

General Assumptions

1. Natural and physical geography criteria are considerably more relevant to open, non-intensive integrated fish/crop farming systems.
2. Intensive systems depend on accessibility to input (feed/seed) and output markets (large urban areas demand).

Sub-Models Assumptions

1. Accessibility infrastructure sub-model
    a. Inland water navigation is processed as polygons, infrastructure network lines.
    b. Considered navigable river segments have *Strahler* number[13] > 7.
    c. Navigation is assumed for small to medium cargo crafts.
    d. Road travel time/cost is modelled for cargo freight, tertiary and local traffic roads are not included; country road network conditions are poor[14].
2. Demand/market sub-models
    a. Urban areas - Population density above 1500 h/k² and area larger than 20 km². Accessibility calculated to major roads (polylines) intersection points with urban areas (polygons). Medium or less dense urban fabrics might not be accounted as substantial markets.
3. Demand/Farmgate sales sub-model:
    a. Uses population density classes and does not account for purchasing or acquisitive power.
4. Physical Geography:
    a. Fish yield (temperature) and soil data are from original study (1997).

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[13] https://www.jayconrod.com/posts/66/the-strahler-number
[14] https://dlca.logcluster.org/display/public/DLCA/2.3+Cameroon+Road+Network

b. Soil/slope sub-model is used for small scale extensive, semi-intensive, pond systems.

c. Slope data is used individually for intensive commercial closed systems.

5. Inputs sub-models' assumptions:

a. Crop – products/by-products can be used as feed or as raw materials for feed mills.

b. Livestock - considered for organic fertilization and/or feed ingredients.

Suitability/Potential Modelling Assumptions

1. Non-intensive open farming systems:
    c. biophysical criteria weight the most on low input systems.
2. Intensive closed Catfish farming systems:
    a. Are not dependent on soil characteristics.
    b. Have lower dependency on water resources (reuse).
3. Large Water Bodies (LWB) Intensive Tilapia farming systems:
    a. The defining location factor is the presence of permanent water.

CONSTRAINTS

- Data gaps must be taken in consideration e.g., bank agency locations (OpenStreet Map)
- Protected area constraints as exclusive are disputed. The type and level of restriction in place is not considered and socio-economic benefits can outweigh protection concerns.
- The definition of thresholds and classification (value judgement) for
    - Buffer distance to/from roads.
    - Buffer distance to/from banks.
- A ser of assumptions are inherited from in IT access mobile broadband coverage maps estimation.
- Accessibility urban classification threshold 1500 hab, area > 20 square kilometres:
    - Quite different urban centres weigh the same e.g., N'Djaména and Sahr.
    - Less densely populated and smaller urban centres are not considered.

RESULTS

Spatial decisions involve a set of alternatives and multiple assessment criteria. GIS-MCDA proposes a method to convert and combine spatial data, and decision-makers criteria to attain evidence for an informed decision. More importantly, it provides an auditable and replicable model, improves communication, offers diverse problem and solution standpoints, and helps refining specification and/or criteria.

From a critical standpoint, we can state that while data analysis and evidence gathering through GIS modelling can contribute to support decision-making processes, a more complex set of socioeconomic, political, cultural, ethno-anthropological aspects, and power relations shape and govern most spatial decision-making.

Modelling is also as good as the input data. Its quality and reliability support the extent to which conclusions can be trusted, and these are just as sound as the analysis conducted. From that prism, specification and objectives define assumptions and approximations, and can always produce distinct answers.

The suitability analysis for the analysed fish farming systems provides mapping at distinct scales.

Catfish and Tilapia Extensive/semi-intensive and integrated small-scale farming systems

Highest location score areas are in the south in the Sudanian AEZ: Mayo-Kebi, Logone, Moyen-Chari, Tandjilé and Mandoul regions. There is prominence to the east of the city of Moundou in the Logone and Mayo-kebi regions. Lower score but suitable areas shown in the southern Sahelian zone, in Guerá, Salamat and Sila regions. The northern two thirds of the country are unsuitable.

The ***location score filtered using asset wealth index*** bellow national average classifies the lowest income suitable areas in south regions, and to some extent within southern parts of Sahelian zone regions Guerá and Chari-Baguirmi. Mapping at department level mean values highlights the southernmost regions: Mayo Kebbi Ouest, Logone occidental/Oriental, Mandoul and part of Moyen-Chari. The top location score districts are Lac Wey, Guéni, La Nya Pendé and Kouh Ouest.

Non-intensive integrated systems priority score is a subtraction of the normalized AWI to the location score. Priority mapping at department level draws attention to the southern Logone

Oriental and Occidental, The Mayo-kebi Ouest, and southern areas of Tandjilé and districts of Mandoul. The city of Moundou appears as central to a fish farming potential zone.

Intensive farming systems using closed/semi-closed-circulation technologies (re-circulating tanks, raceways, flow-through systems, and ponds) are less dependent on natural or biophysical criteria and pose smaller environmental risks due to controlled exchange between farm and environment. Final location mapping, optimal theoretical investment sites, are within exclusive criteria of distance to major roads, access to IT (mobile broadband coverage) and distance to bank agency.

Most suitable score areas are in the south Sudanian AEZ, in a Moundou centred zone, but also to a smaller extent in the southern part of the Sahelian AEZ.

Final location mapping emphasizes southern urban centres, Bongor, Pala, Moundou and Sahr, and a smaller area in Am Timan. Interpretation must consider data gaps, finance access (bank agencies) data might not be exhaustive, complete, and accessibility to urban areas weights the same cities like Abéche, Moundou and Sarh, as the capital N'Djaména.

For the ***Tilapia open intensive systems*** using open-net pens/cage techniques the defining factor is the presence of permanent waterbodies. Highest location score areas are to the immediate north of N'Djaména, around Moundou, and in small areas bordering Cameroun and the Central African Republic.

Final location mapping at large scale using permanent waters, points locations in lakes and major rivers:

- N'Djaména area and the Chari and Logone rivers bordering Cameroun.
- Lake Chad region, water, wetlands, and the Chari River.
- Lake Iro.
- The Logone River in the northwest of the city of Bongor and close to the Maga reservoir.

RECOMMENDATIONS

Caution and examination should prevail in aquaculture development planning in Chad. interventions must consider a wide range of factors affecting sustainability and impacts: environmental, health and disease, land and water competition, but proposals should also be highly customized according to local specificity and based on and objective and impartial assessment of ethnic, cultural, religious, socio-political diversity and conflict.

Water is scarce and precipitation irregular for most of the country, rendering resources highly variable and disputed. Political and socio-economic change, and conflicts have disrupted lake and wetlands socio-ecosystems, and its traditional customary governance. Violent, armed conflict and military repression caused large population displacement, disappearance of economic outlets and changes in herd routes, amplifying conflict factors like variations in floodplain areas in the last 5 decades.

Developing a disputed scarce resource based activity like fish farming, in a setting marked by demographic pressure, diversity of resources and seasonal fluctuations, plurality of actors and complexity of rights of exploitation and high conflict potential, must be very well framed and informed, to be adapted to specific local conditions. Cage systems in waterbodies particularly face extraordinarily complex biophysical, social, political, governance and security challenges.

Development projects and fish farming policies must so reflect on a series of circumstances that are found, in different degrees, throughout the Sahelian region, those are:

- Land tenure issues.
- Ethnic diversity.
- Disputes for access and control of resources.
- Settlement disruption and population displacement due to armed conflict.
- Economic agreements between States and large private development projects (Iocchi, 2020).
- Increasingly problematic transnational mobility for multinational ethnic groups.

Open systems exchange with the surrounding environment, transferring waste, chemicals, parasites, disease, and have a high potential for fish escapes. Endorheic shallow lakes can amplify problems like eutrophication, reduction in dissolved oxygen, production of toxic microorganisms, toxicity on aquatic ecosystems, and disruption of fish assemblage in the wild or genetic pool impact.

In more advanced fish farming countries in the SSA region there is evidence of harmful organic and chemical effluents, and the direct discharge of untreated fish farming waste waters in river streams (Albine et al., 2021; Bouelet Ntsama et al., 2018) which can be even more impacting in water scarce environments like most of Chad’s territory. Sector development planning should also consider health and disease monitoring and management must, with surveys, monitoring, diagnostic, and guidelines on biosecurity.

Besides the reductionist modelling consideration of physical geographical conditions, supply, demand, infrastructure and accessibility, the awareness of social-cultural, ethnic, and political context must guide proposed interventions. An integrated comprehensive approach can result in successful sustainable adapted proposals, targeting customized systems and models which can positively impact poverty, hunger, malnutrition, food security, and/or can lead to high return on investment on commercial aquaculture systems and job creation.

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