FRESH WATER FISH FARMING SUITABILITY ASSESSMENT – CAMEROUN

Draft version

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Abstract

The aim of this report is to document a fresh and warm-water fish farming systems suitability assessment for Cameroun, for the African Catfish and Nile Tilapia species. This aquaculture geographic information systems (GIS) multi-criteria decision analysis (MCDA) study is under the scope of the support to the updating and operationalization of the "*Plan de Développement Durable de l'Aquaculture au Cameroun (PDDAC)*" and the project "*Projet de Développement des Chaînes de Valeurs d'Elevage et de la Pisciculture (PD-CVEP)*".

Cameroun fish farming context and background were assessed through literature review. The modelling methodology developed from Aguilar-Manjarez and Narh 1998 - A strategic reassessment of fish farming potential in Africa. The GIS-MCDA approach uses weighted factors including market demand, poverty, infrastructure, inputs livestock and crops, physical geography (soil, slope, water availability) potential yield, and photovoltaic (PV) energy generation potential. Constraints or exclusive criteria were applied distinctly to different farming system models: 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 final mapping outputs which indicate the potential for high return on investment optimal sites, aimed at intensive fish farming for both closed catfish (tanks, raceways, ponds, recirculating aquaculture systems) and open tilapia (large water bodies) systems, and zoning at regional and *départment* 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: *Littoral* Douala, *Centre* Yaoundé, *Ouest* and *Nord-Ouest* Bafoussam/Bamenda, Garoua *Nord*, and Maroua *Extrême-Nord*. Using PV potential as an intensification measure classifies coastal areas with lower scores but doesn't change the previously identified pattern. Final maps identify most suitable areas around major urban regions in the country, Youndé, Douala, Bafoussam/Bamenda at a smaller scale Maroua (*Extrême-Nord*).

Tilapia open intensive systems in large water bodies (LWB) using open-net pens/ cage techniques, highest location score areas can be found in *Ouest*, *Nord-Ouest*, *Littoral* and *Centre*, with the top potential sites locating in the proximity of a Douala/Bouea, Yaoundé, Bamenda/Bafoussam triangle:

- Bamendjing Lake – *Ouest*, *Nord-Ouest* Regions.
- Barombi Mbo Lake – *Sud-Ouest* Region.
- Song Loulou dam, Edea dam and Ossa Lake – *Littoral* Region.
- Natchigal dam – *Centre* Region.

For the open non-intensive integrated fish/crop farming systems highly suitable areas can be found in western and coastal regions. Filtering using asset wealth index (AWI) bellow national average, *Sud-Ouest* and *Nord-Ouest* show the highest scores, but smaller areas can be spotted in other regions, (*Sud, Littoral, Est*, and *Adamaoua*). Mapping at *départment* mean values reveals a decreasing pattern from the cost to the interior, with top score class:

- *Sud-Oest* (Manyu, Kupé Manenguba, Ndian, Meme).
- *Littoral* (Moungo).
- *Ouest* (Mifi).

A non-intensive systems priority index (AWI - location score) highlights *départments*:

- *Sud-Ouest* (Manyu, Kupé Manenguba, Ndian, Meme).
- *Nord-Ouest* (Menchum).
- *Est* (Haut–Nyong, Kadeï, Boumba-Et-Ngoko).

Caution is recommended over sustainability, for both environmental aspects, and health and disease management and monitoring. Interventions should also be outlined recognizing ethnic and cultural diversity and considering existing resource competition issues, prone to conflict problems in the country and region.

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

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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 Cameroun.

Departure questions can be 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 Cameroun 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 considerably evolved since the 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 states or regions 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, which implies distinct criteria combination and weighting, and is conditioned by a different 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, and alternative energy potential, 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).
5. Photovoltaic (PV) potential – Closed systems Intensification potential using alternative energy.

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.

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.

[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).

Integration of GIS and MCDA provides a replicable model, improves communication between project participants or decision-makers, can offer a different 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

According to OECD-FAO Agricultural Outlook 2021-2030 (OECD & FAO, 2021), fish production, trade and consumption all contracted in 2020 due to COVID19. But in the 2021–2030-decade, world fish production was projected to grow at 1.2% and aquaculture at 2.0% p.a., lower growth rates compared to the previous decade reflecting policy changes in China (sustainability and environmental protection), increased feed cost, reduced productivity gains, and competition for land. By 2030 aquaculture is anticipated to 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 is predominantly inland and freshwater. The types of 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

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

water competition, employment, value chain growth and risks like climate change impacts or social and regional conflicts are also merely mentioned.

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

CAMEROUN

According to FAO Fishery and Aquaculture Country Profiles[3] (FAO Fisheries and Aquaculture Division, 2022) there is an expanding fish demand in Cameroun, national average fish consumption was estimated at about 18.4 kg per person in 2017, and consumption estimated 2016 545.000t/y with capture production (around 282.000 tonnes (2018)) covering less than 43%.

Aquaculture production was estimated at 2 500 tonnes (2019), essentially from North African catfish and Nile tilapia species.

The promotion and development of sustainable commercial aquaculture is defined as a government priority (DSCE1, PNIA2, Stratégie MINEPIA, 2011 and 2014 and Vision horizon 2035). The aquaculture development strategic framework was defined in 2003 and in 2009, with the "Plan de Développement Durable de l'Aquaculture au Cameroun (PDDAC)" supported by FAO(FAO UN, 2022b, 2022a). Since then, there has been slow steady progress, aquaculture production grew from 1,593 tonnes to 2,340 tonnes between 2013 and 2018 (PNIA, 2014-2020) with the expansion of new production systems (cages, and tanks), and after 10 years the plan is being updated and linked with other strategies

[3] https://www.fao.org/fishery/en/facp/cmr?lang=fr

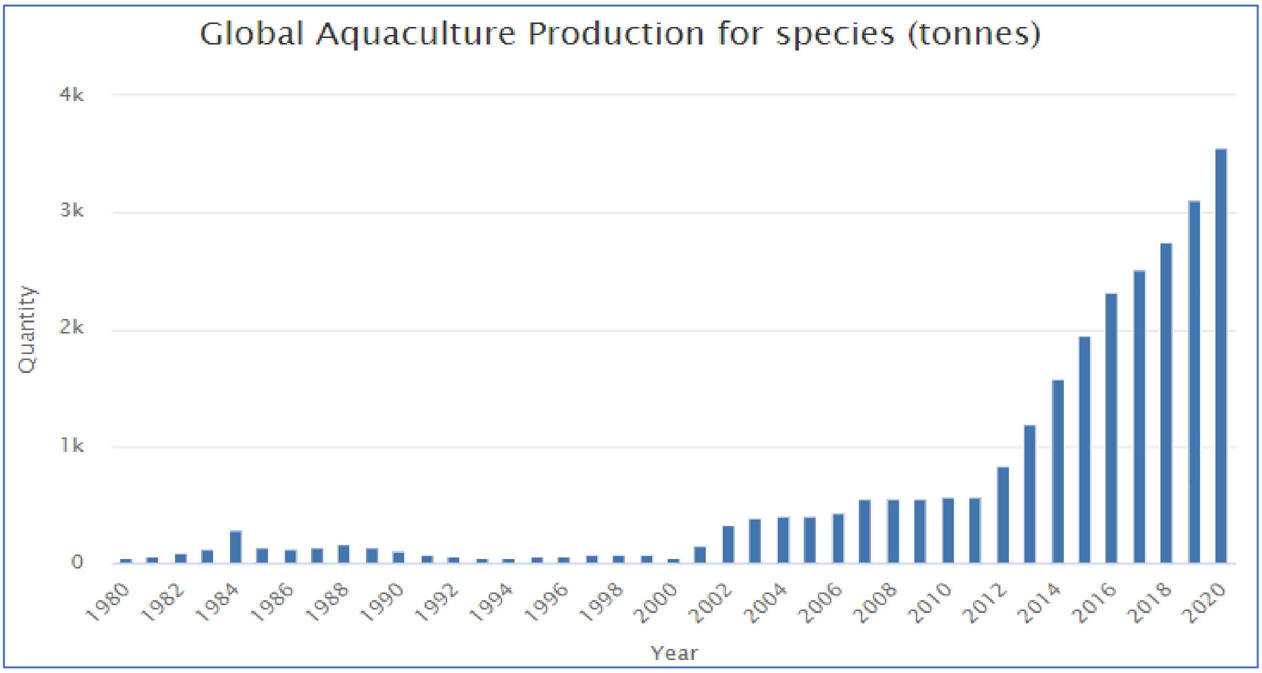

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Figure 1 - Aquaculture production - source: FAO Fishery and Aquaculture Statistics

With the advantage of extensive inland water resources, favourable natural conditions, policies and political support, production shows a stable growth since 2011 (Fig. 1), but existing literature points to significant infrastructural, financial, and technical constraints to expansion (Albine et al., 2021; Jeh Mkong, 2018; Junie Albine Atangana Kenfack et al., 2019; Kenfack et al., 2019; Maimoune et al., 2022). There is a recognized insufficiency in fish feed industries, quantity of quality fingerlings, trained personnel, and lack of control over production technologies, that sum to difficulties in access to finance and land, with a decline on the number farmers being observed in some areas (2015 to 2018) (Maimoune et al., 2022).

Studies suggest the need of recycling of fish farming techniques, improving farmers organization and participatory planning, simplification of licensing processes, facilitation of access to inputs, technical support for pond construction, land acquisition and financing.

Current policies thus propose targeting the development of a commercial aquaculture sector, through the evaluation, update and dissemination of the "*1e Plan de Développement Durable de l'Aquaculture au Cameroun*", the developing an operationalization investment framework and organizing round table of technical and financial partners, with FAO leading technical support and government represented by the *Ministère de l'Elevage des Pêches et des Industries Animales* (MINEPIA) , *Direction des Pêches, de l'Aquaculture et des Industries Halieutiques* (DPAIH). (FAO UN, 2022b, 2022a)

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 currently considered 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 been observed to 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 was found to bring 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, high 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 *départments*.

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 and using alternative solar power/photovoltaic (PV) potential.

- **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. **THE WORLD BANK - World - Photovoltaic Power Potential** (PVOUT) - Global Solar Atlas - https://datacatalog.worldbank.org/dataset/world-photovoltaic-power-potential-pvout-gisdata-global-solar-atlas

8. **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.

9. **AtlasAI**

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

10. **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*[4].

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

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

Measures (WD-OECM): Datasets were Clipped for CMR, merged the several layers and overlapping polygons combined.

Data is edited extracted/clipped using country borders.

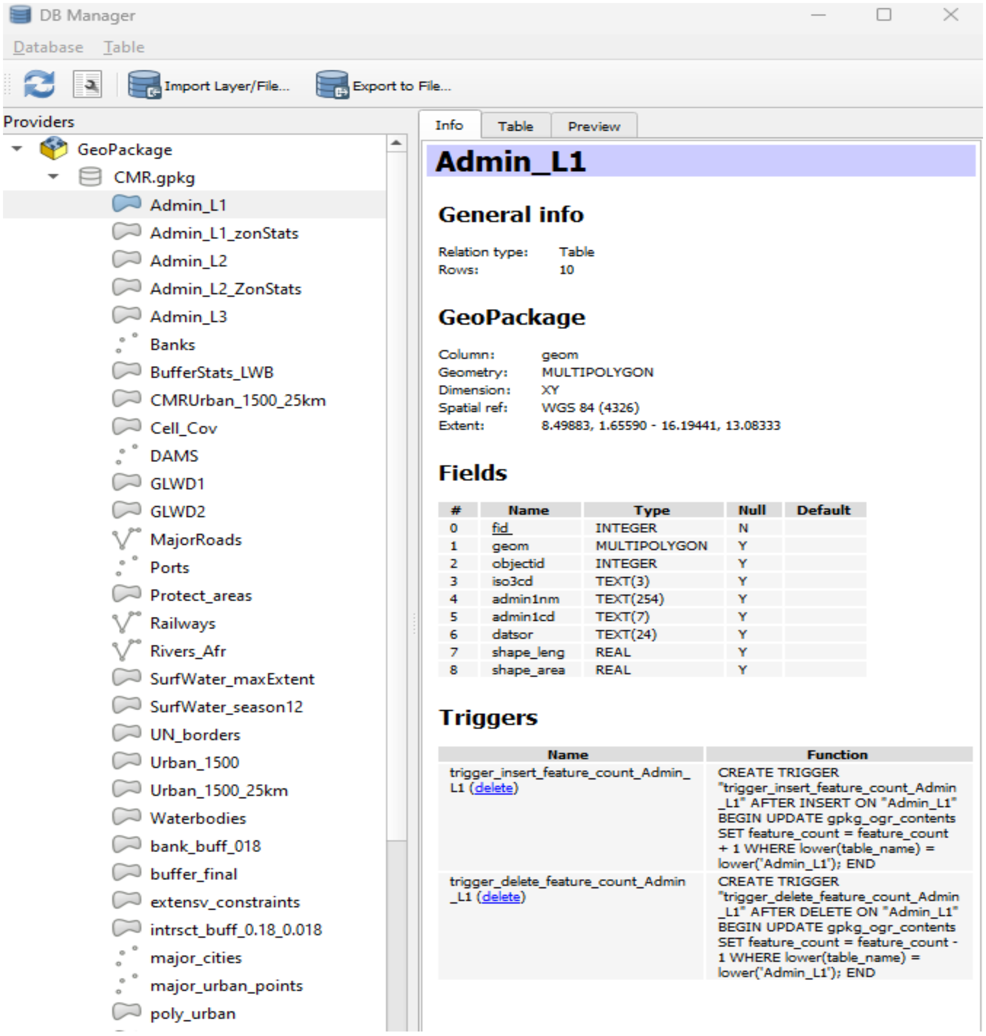

Figure 2 – Geopackage

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[5].
4. Road travel time/cost is modelled for primary/motorway/truck road classes; road network conditions are poor[6].
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.

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

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

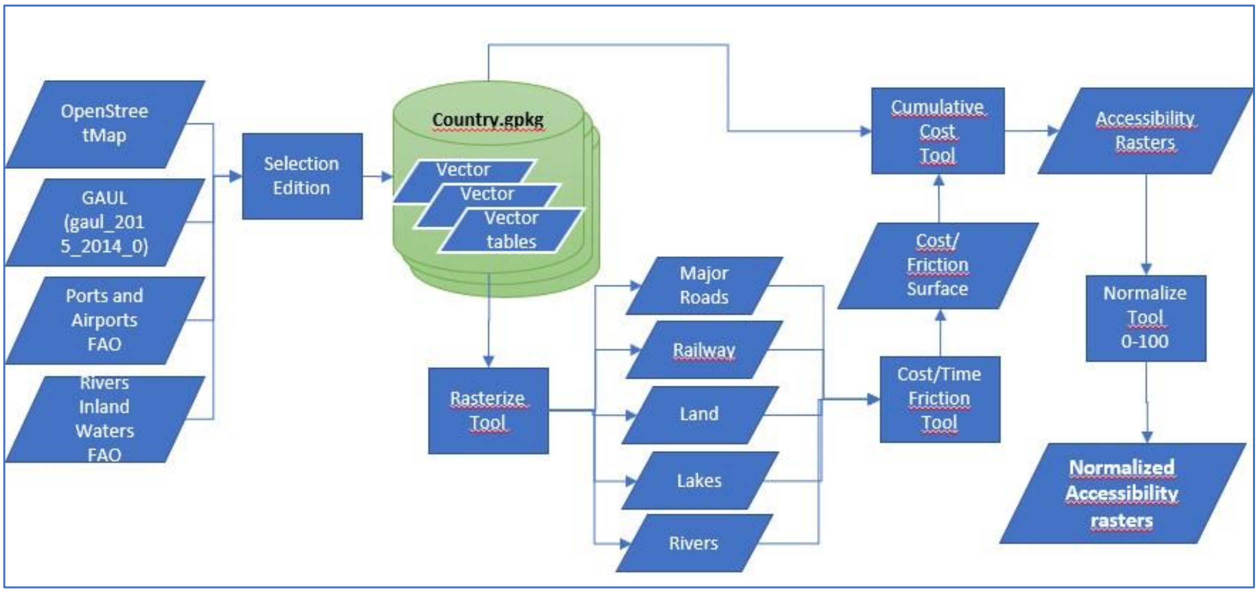

Figure 2 - Accessibility modelling flowchart

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/km², area>25km² is defined to 7 urban regions in Cameroun, calculated using roads layer (lines) intersection points with urban areas (polygons) for a total of 97 access points.

Assuming the existing large 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.

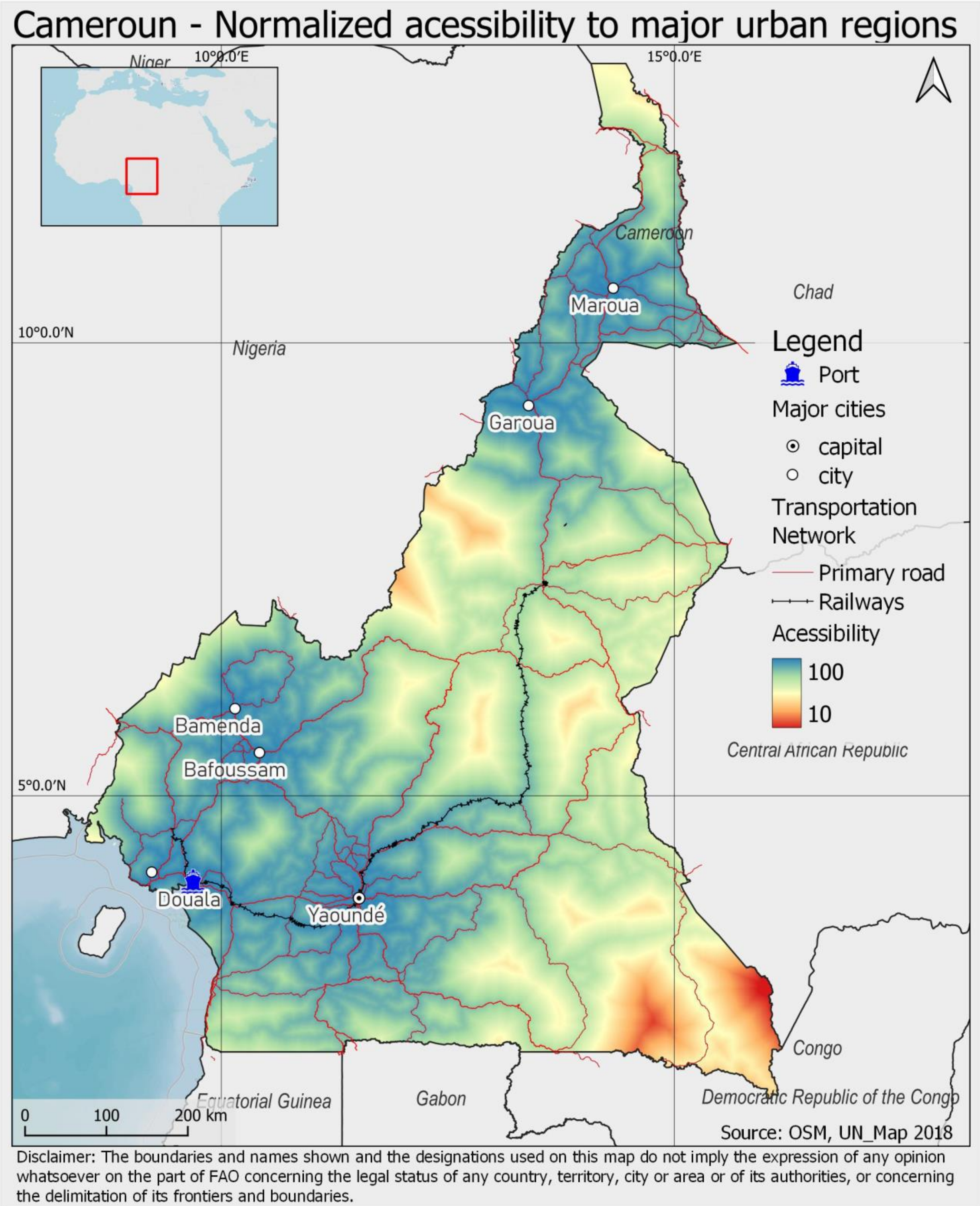

Figure 3 – Accessibility to urban areas map

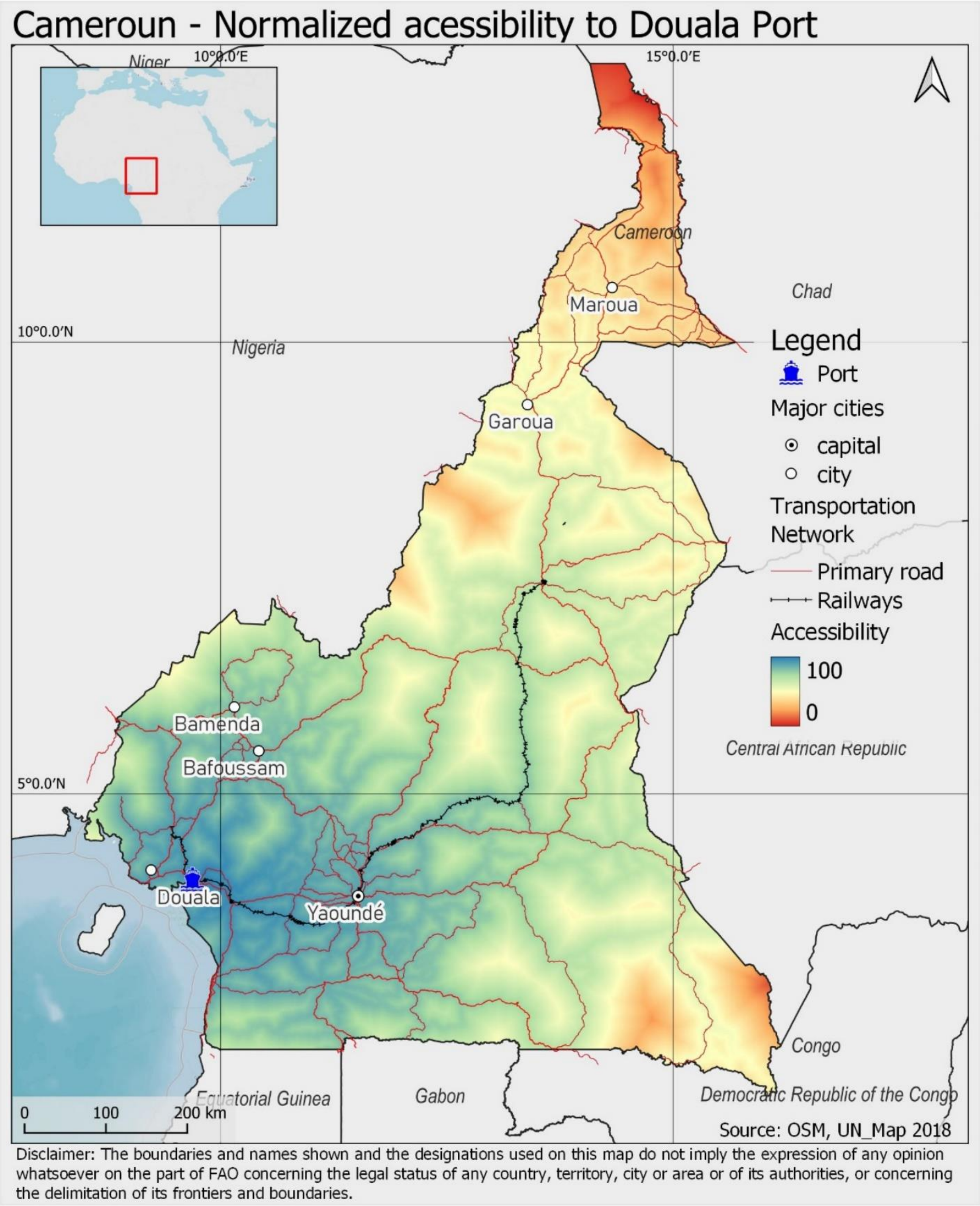

Figure 4 – Accessibility to ports map

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 25km², resulting in a total of 7. 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”>25km².
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 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)

GSW 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. Water temperature is originally estimated using 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 Cameroun and normalized/scaled (0, 100).

There are some gaps in the fish yield datasets that might have some 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.

4.4.2.1 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)

4.4.2.2 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)

4.4.3 Photovoltaic energy generation potential

Closed faming systems intensification is constrained by energy supply. Considering that part of the territory has no grid access and that the existing network has stability and quality issues, modelling inputs an alternative energy source, photovoltaic power potential (PVOUT), average daily total in kWh/kWp, as a measure of intensification potential. Data processing involves:

- ***Clipping*** –to country borders.
- ***Normalization – raster calculator*** – grid scaling normalizing (0-100)
- Raster ***resampling/aligning***.

5. SUITABILITY MODELLING

The zoning effort targets Catfish and Tilapia farming systems technologies that are 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.

Assumptions:

1. Water availability is suitable or very suitable for most of the territory - criteria weighting could be lowered and weighting transferred to farmgate sales.

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 is obtained by way of a simple arithmetic weighted sum (*GRASS r.series tool*) of criteria normalized/scaled grids, theoretically varying from 0 to 100: *("WaterBalance" X 0.5) + ("Soil/Slope " X 0.25) + ("Byproducts" X 0.125) + ("FarmgateSales" X 0.125)*

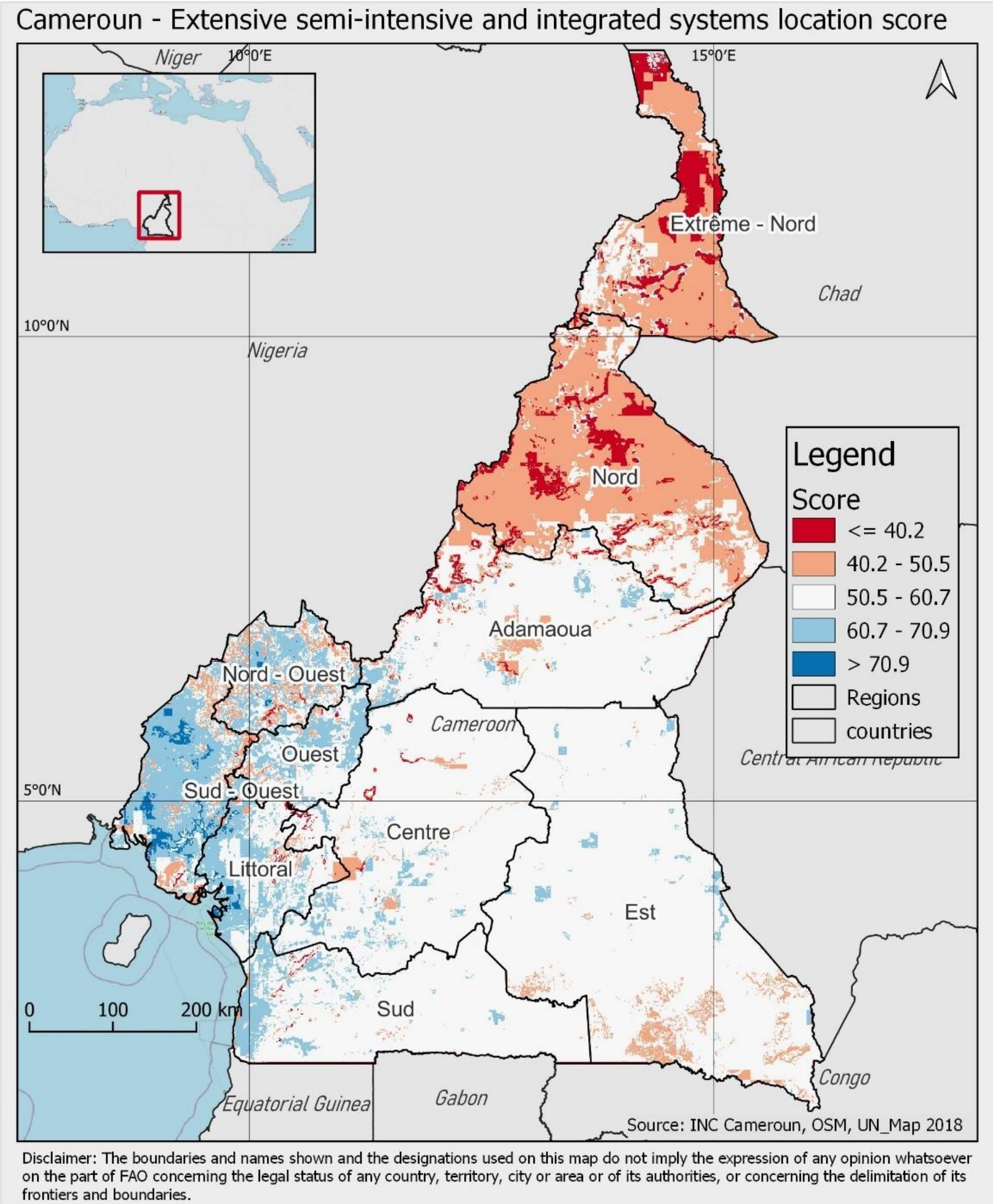

Figure 5 - Non-intensive and integrated systems suitability map

Highly suitable areas are found in western and coastal areas, but to a certain level also in smaller areas in continental regions, where most of the territory has a median suitability. *Nord* and *Extrême-nord* are the less suitable for non-intensive small-scale systems, but low suitability areas can also be found in western regions highlands or in the country southeast.

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'.

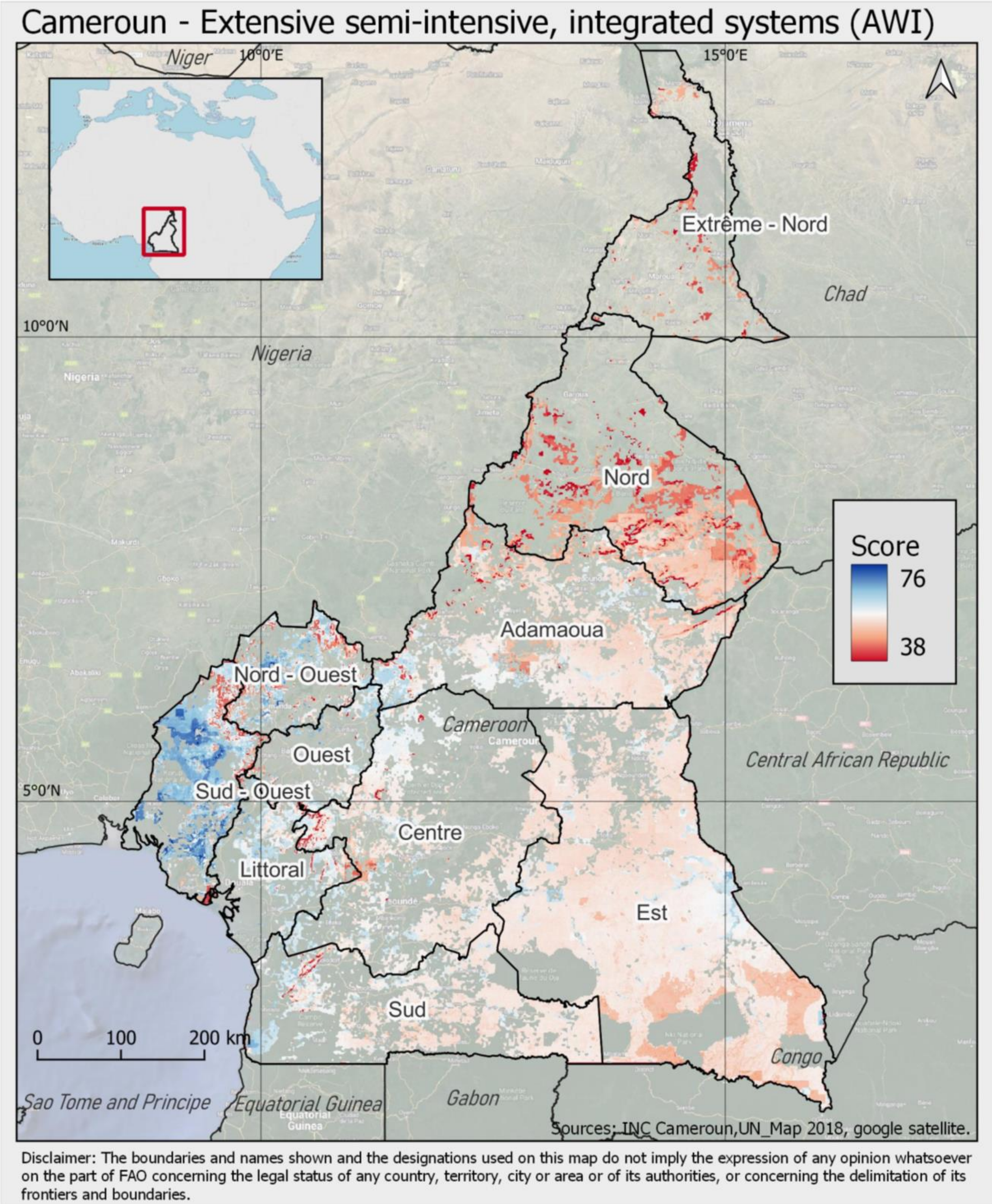

Figure 6 - Non-intensive systems (with poverty) map

Figure 6 allows the classification and identification of the suitable areas where the AWI is below the national average. *Sud-Ouest* and *Nord-Ouest* are clearly identified but smaller areas are also detected in several other regions, like *Sud*, *Littoral*, *Est*, and *Adamaoua*.

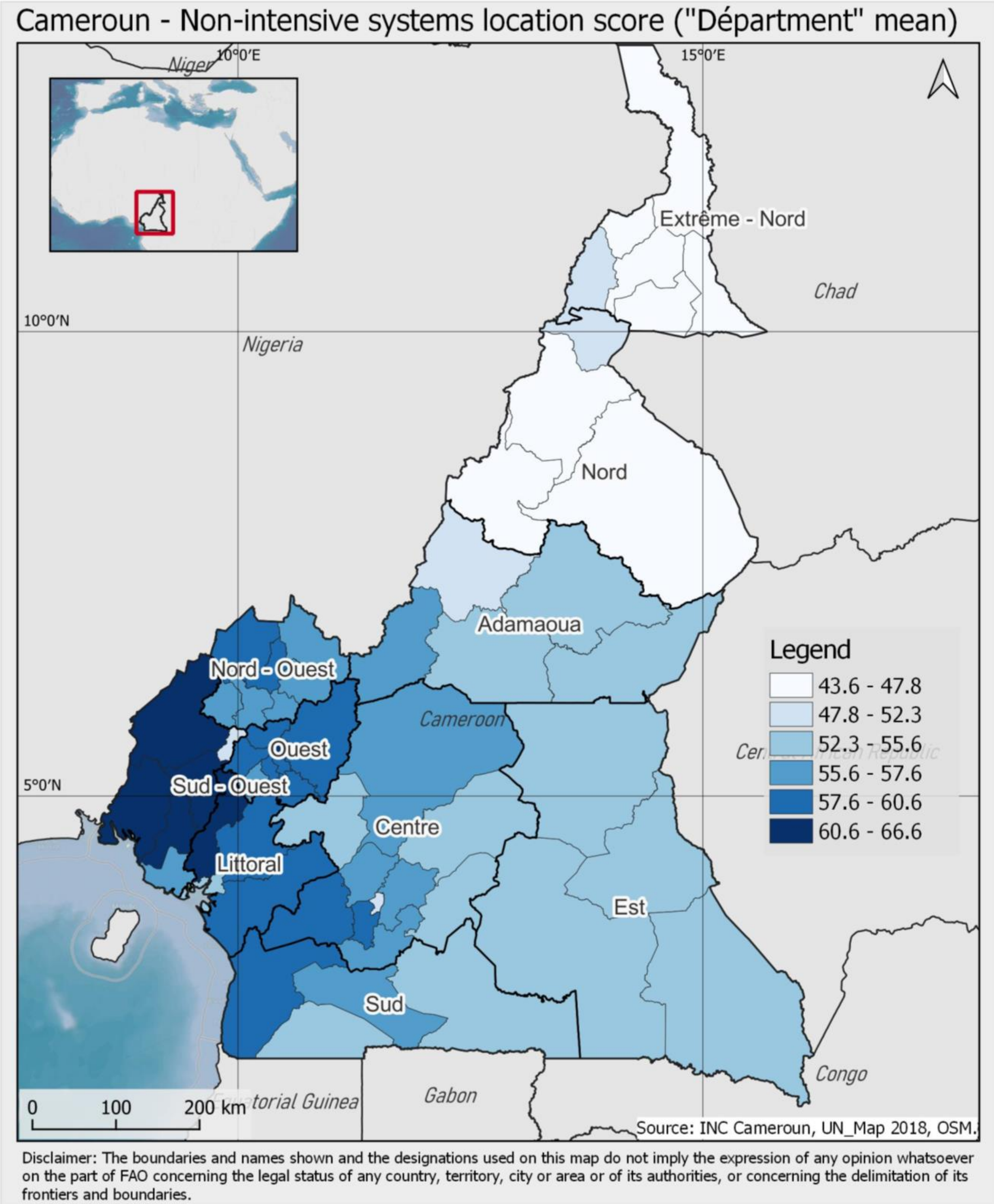

Figure 7 - "Départment" average non-intensive systems location score map

Analysing figure 7, the *départment* average score permits individualizing administrative units for interventions. It reveals *Sud-Oest's* Ndian, Manyu, Kupé Manenguba, Meme, and *Litoral,* Moungo, *départments* with the highest location score and a decreasing pattern from the cost to the interior, with *Nord* and *Extrême-Nord départments* classified as less suitable.

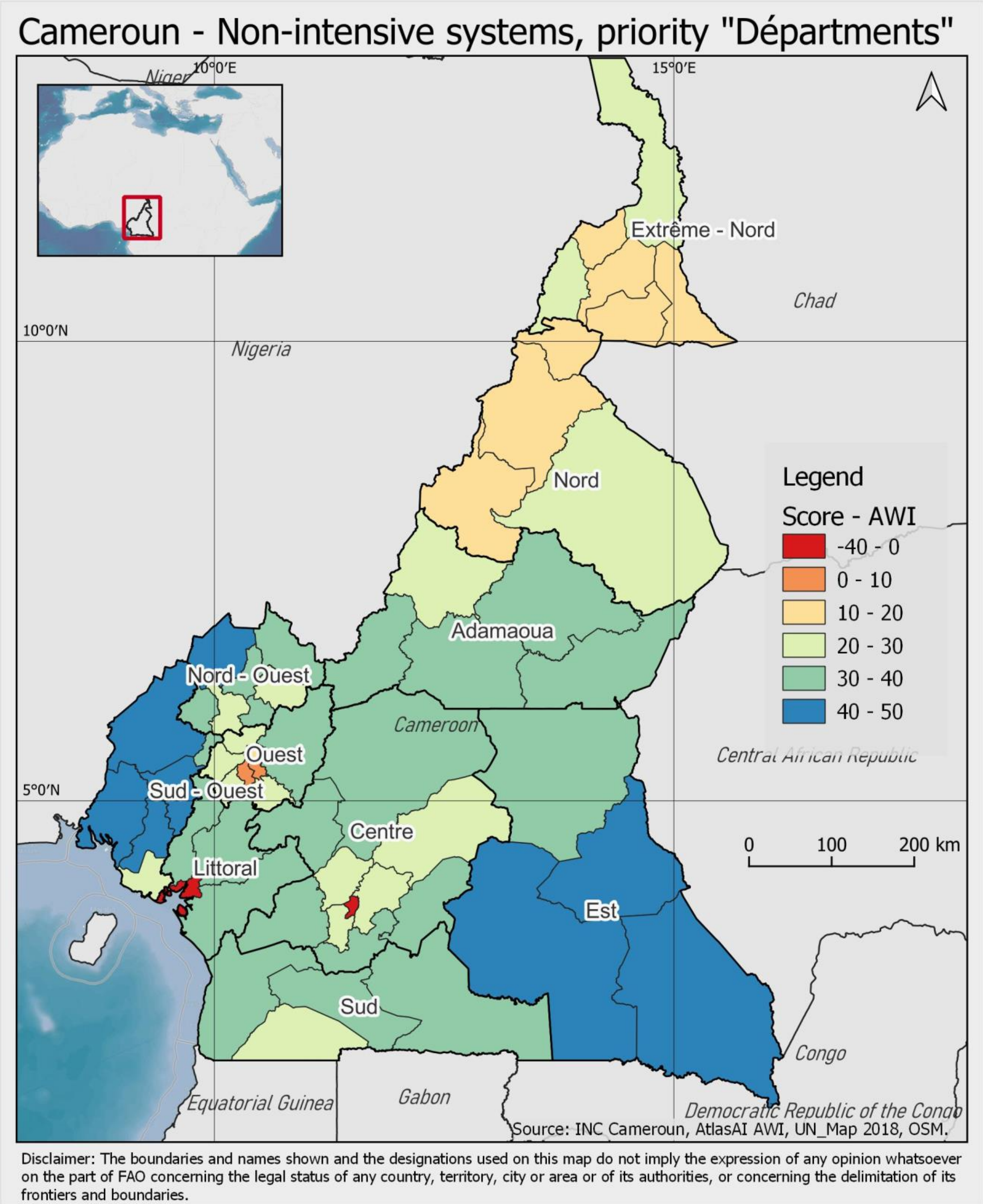

Figure 8 - "Départment" non-intensive integrated systems priority map

Priority is defined by subtracting the normalized AWI to the location score, a high value means a low AWI and high suitability. The measure can be used to classify priority *départments* for interventions. *Figure 8* points to *Sud-Ouest's* Ndian, Manyu, Kupé Manenguba, Meme and *Nord-Ouest* Menchum as priority, but also identifies all *Est* region (Kadeï, Haut-Nyong, Boumba-Et-Ngoko) for targeting food security and income diversification fish farming systems.

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

Intensive closed farming systems are limited by poor and unreliable energy distribution networks (Satia, 2017). Solar power/photovoltaic (PV) can supply operational needs [7] of closed systems pumps and aerators, to provide oxygen, to move water into and through the system, and to purify the water. Suitability assessment modelling introduces PV as intensification potential.

It is assumed that closed systems techniques using ponds, tanks, RAS, flow through and recirculation are considerably 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.[8]

Assumptions:

1. There is enough water availability in most of the territory (even without considering ground water).
2. Closed intensive systems are not dependent on soil characteristics.

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

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

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.
f. Slope - terrain suitability.
g. Photovoltaic (PV) energy potential.

Constraints:

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

Final maps exclusive criteria:

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

The exercise presents alternative outputs with and without PV.

5.2.1 Location score (without PV)

The location score is obtained by way of a simple arithmetic weighted sum (normalized/scaled grids), theoretically varying from 0 to 100, with the following weighting: *(“Accessibility MajorUrbanAreas” X 0.5) + ("WaterBalance" X 0.15) + ("potential Yield" X 0.15) + (“CropsInput” X 0.075) + (“LivestockInput” X 0.075) + ("Slope " X 0.05)*

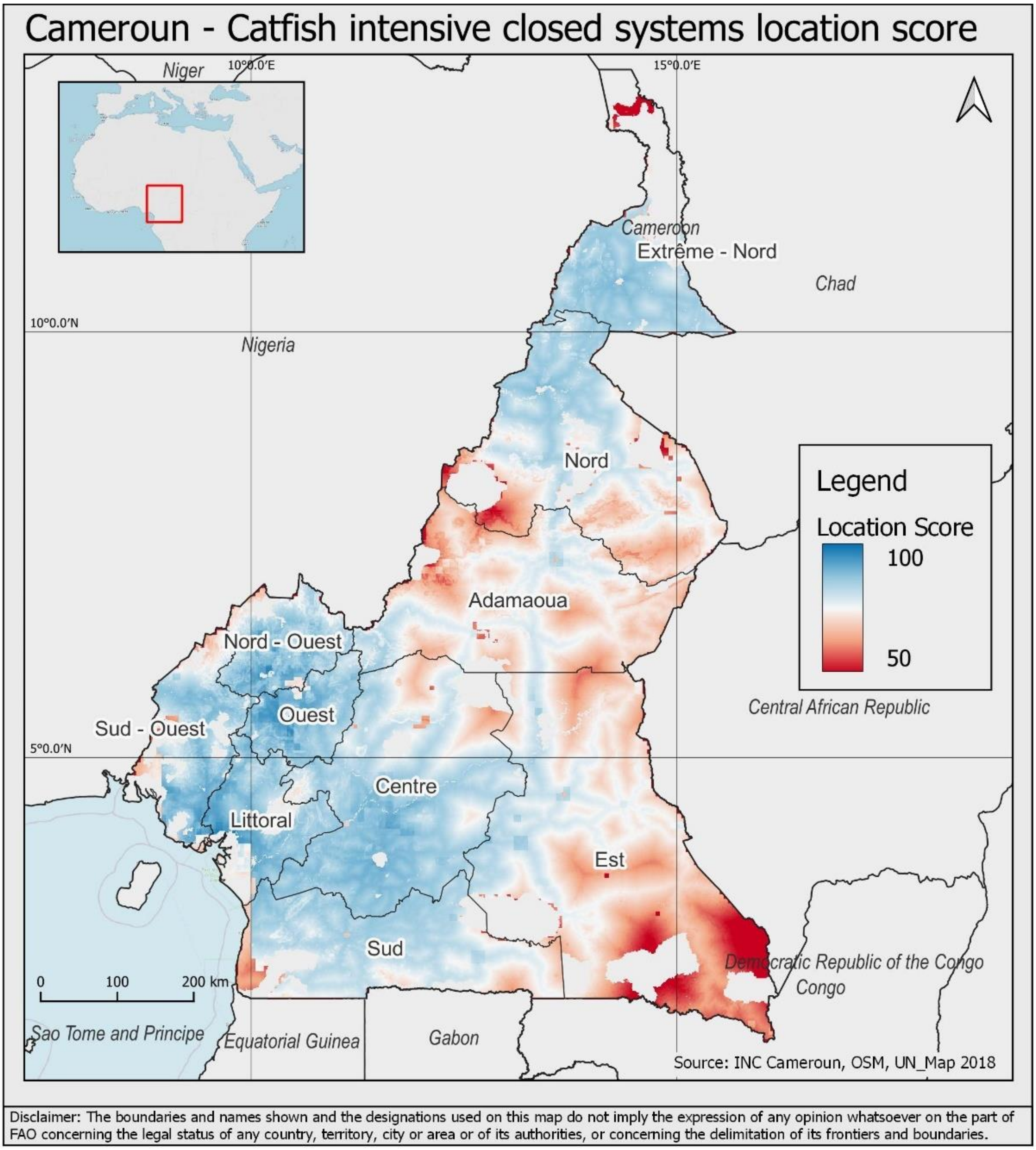

Figure 9 - Intensive closed catfish systems location score map

Since the demand factor is of major importance, intensive closed commercial farming systems suitability spatial pattern follows output markets, large metropolitan/urban regions. *Littoral* Douala, *Centre* Yaoundé, *Ouest* and *Nord-Ouest* Bafoussam/Bamenda, Garoua *Nord,* and Maroua *Extrême-Nord.*

5.2.2 Location score - with PV

The location score is obtained by way of a simple arithmetic weighted sum (normalized/scaled grids), theoretically varying from 0 to 100, with the following weighting: *(“Accessibility MajorUrbanAreas”x 0.4) + (PVOUT x 0.10) + ("potential Yield"x 0.15) + (“CropsInput” x 0.1) + (“LivestockInput” x 0.1) + (("WaterBalance" x 0.1) + ("Slope "x 0.05)*

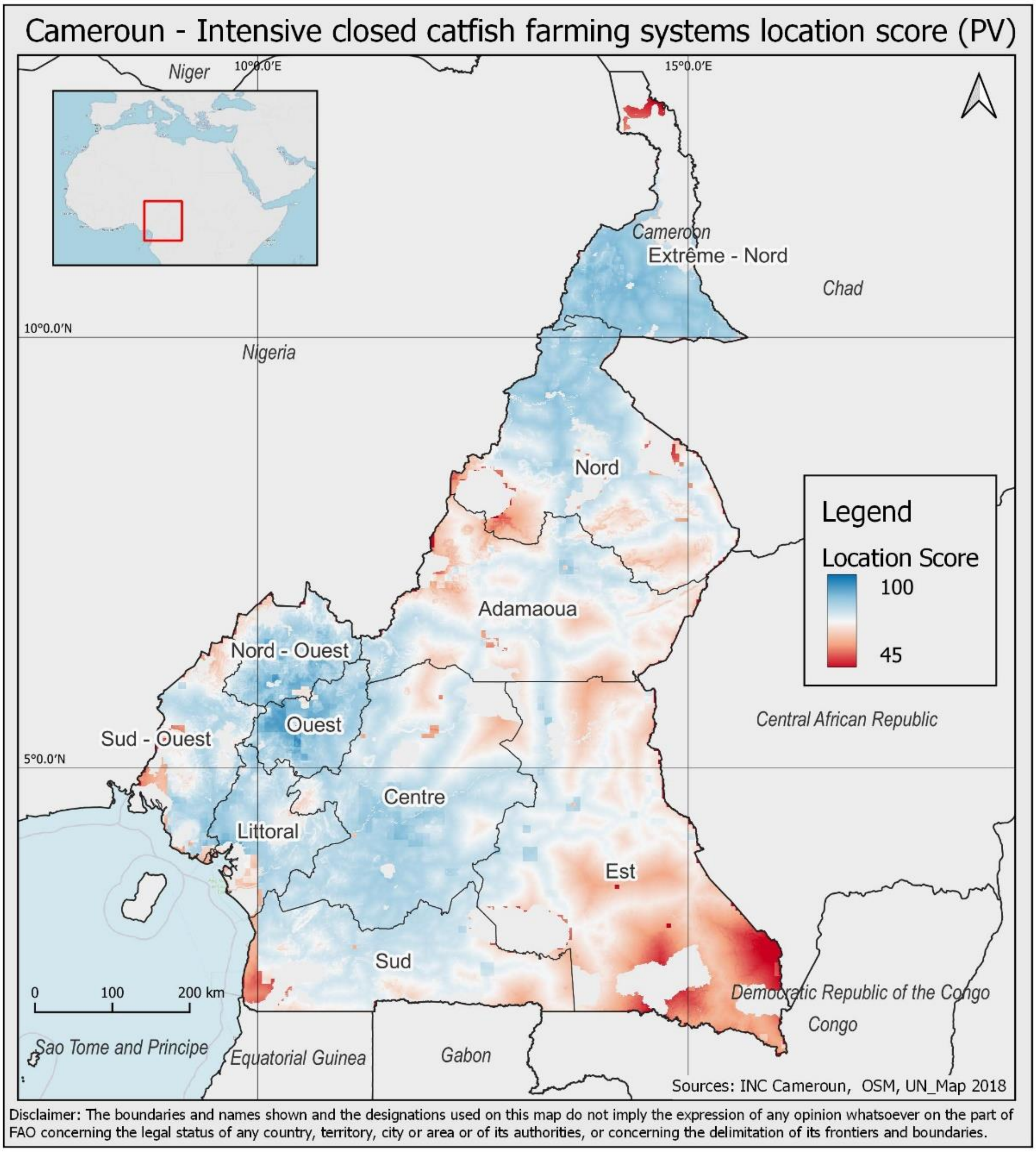

Figure 10 - Intensive closed catfish farming systems intensification potential (PV) map

The location score was normalized after applying both constraints and UN map country border.

Using PV energy generation as location factor doesn't change the previous pattern although coastal areas score lower, giving more weight to *Ouest* and *Nord* and *Extrême-Nord* regions.

The market/demand criteria using population density can also be misleading when urban population concentration *per se* does not guarantee market purchase power for intensive large-scale production.

5.2.3 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.

Access to finance is defined as a linear distance to a bank agency.

Final mapping follows the subsequent procedure:

- ***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 90^{th} or the 95^{th} 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)))

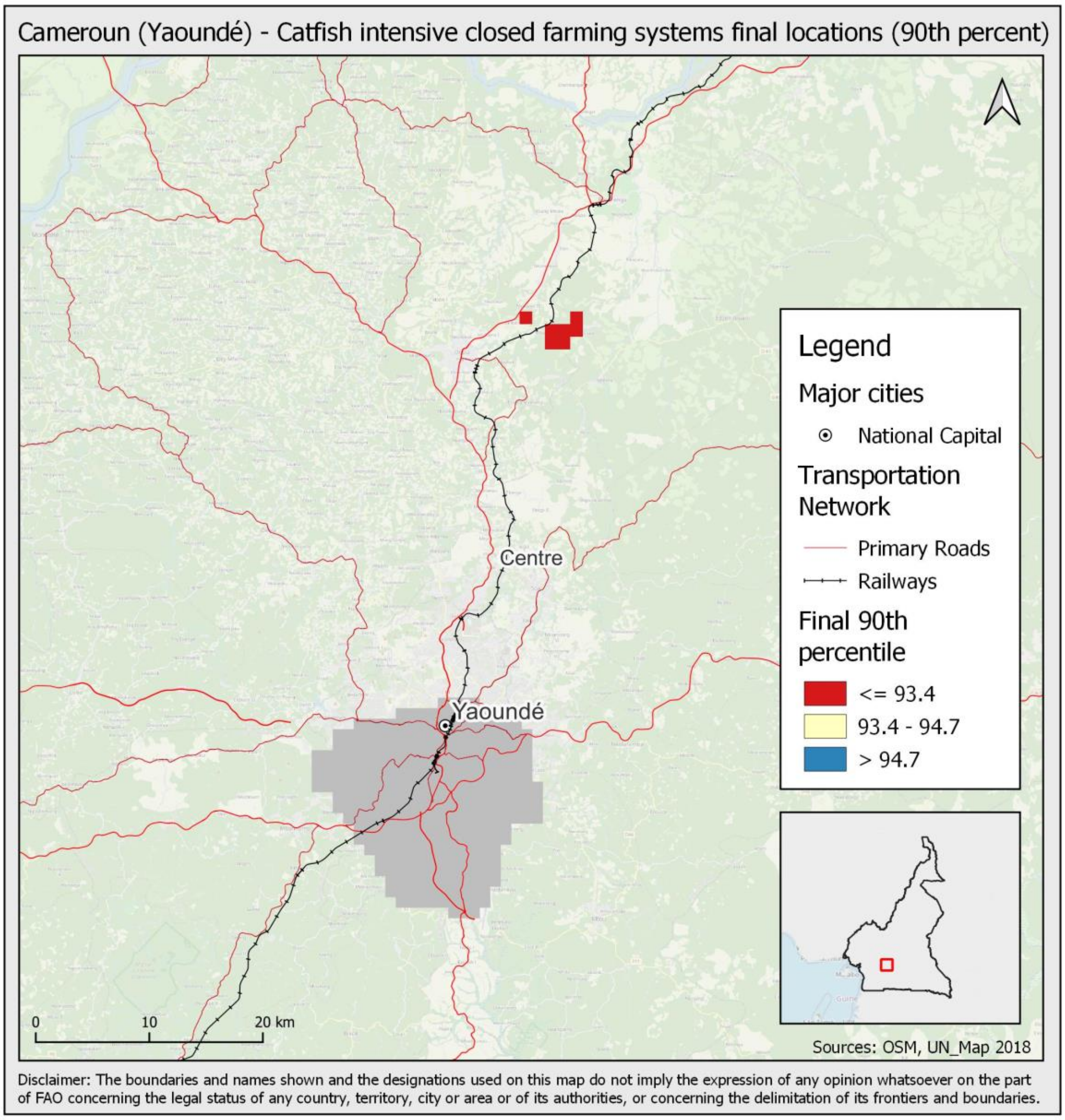

Figure 11 - Yaoundé - Intensive closed systems suitability map – 90th percentile

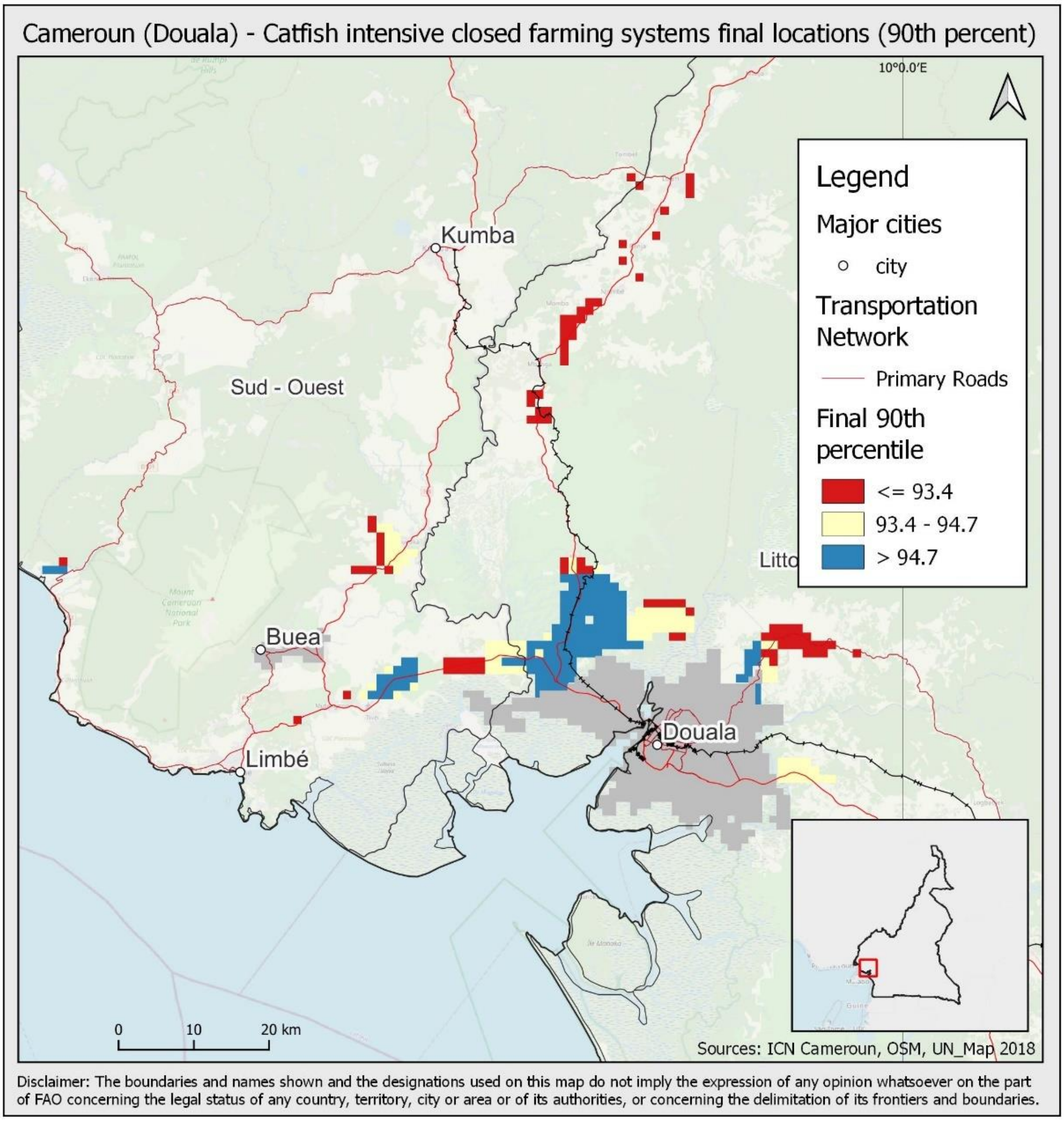

Figure 12 - Douala - Intensive closed systems suitability map – 90th percentile

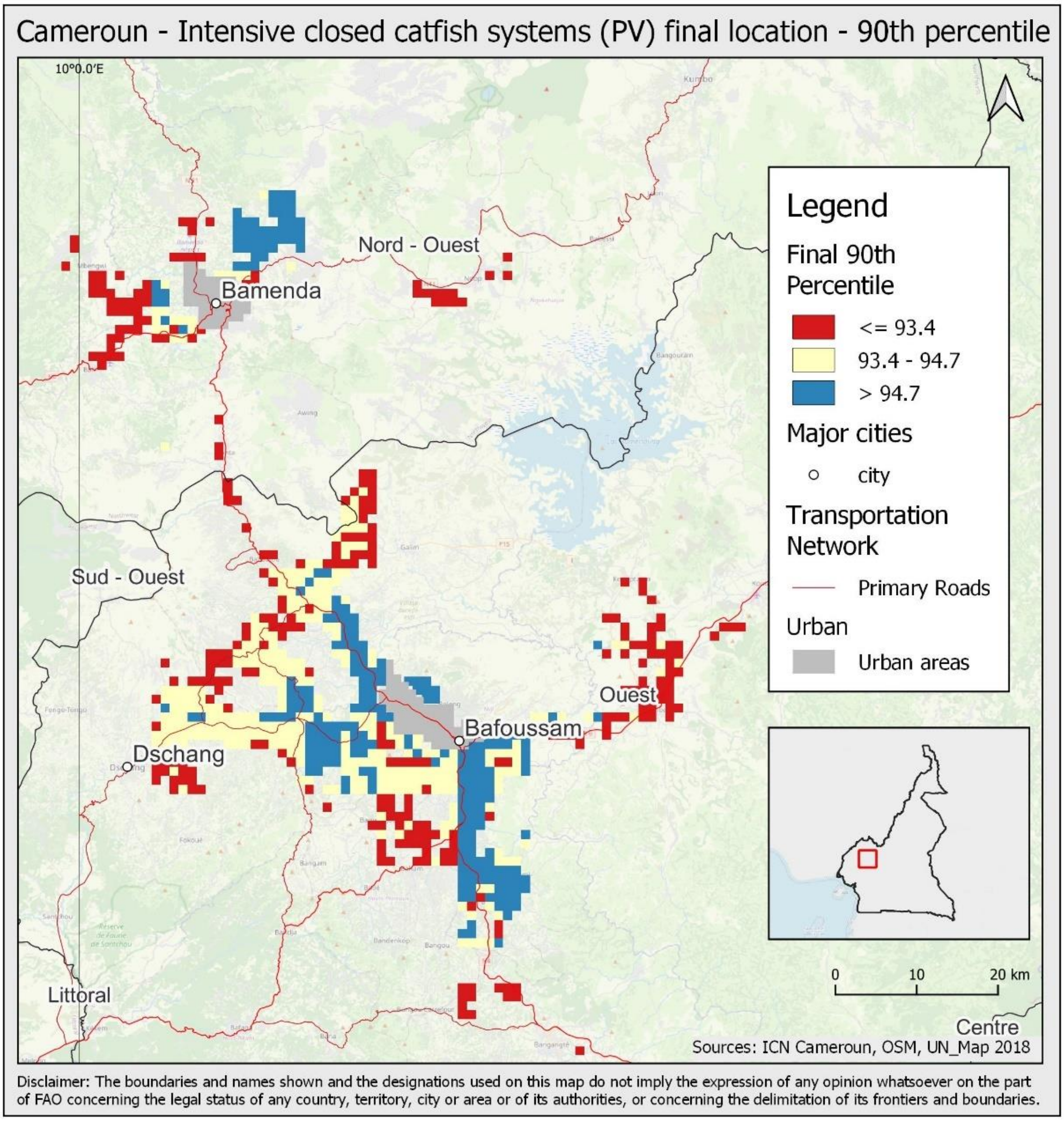

Figure 13 - Bafoussam - Intensive closed systems suitability (PV) map – 90th percentile

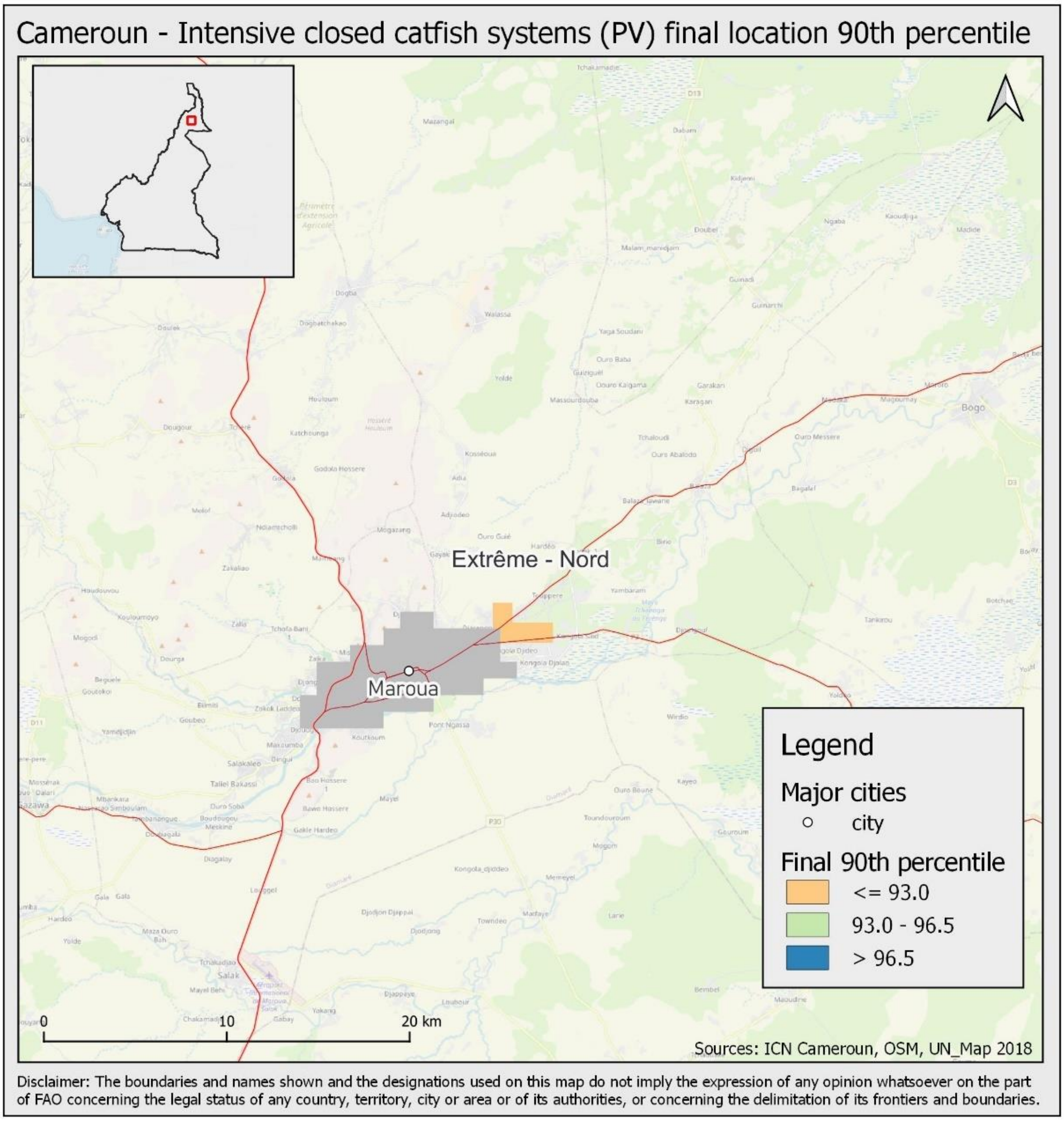

Figure 14 - Maroua - Intensive closed systems suitability (PV) map – 90th percentile

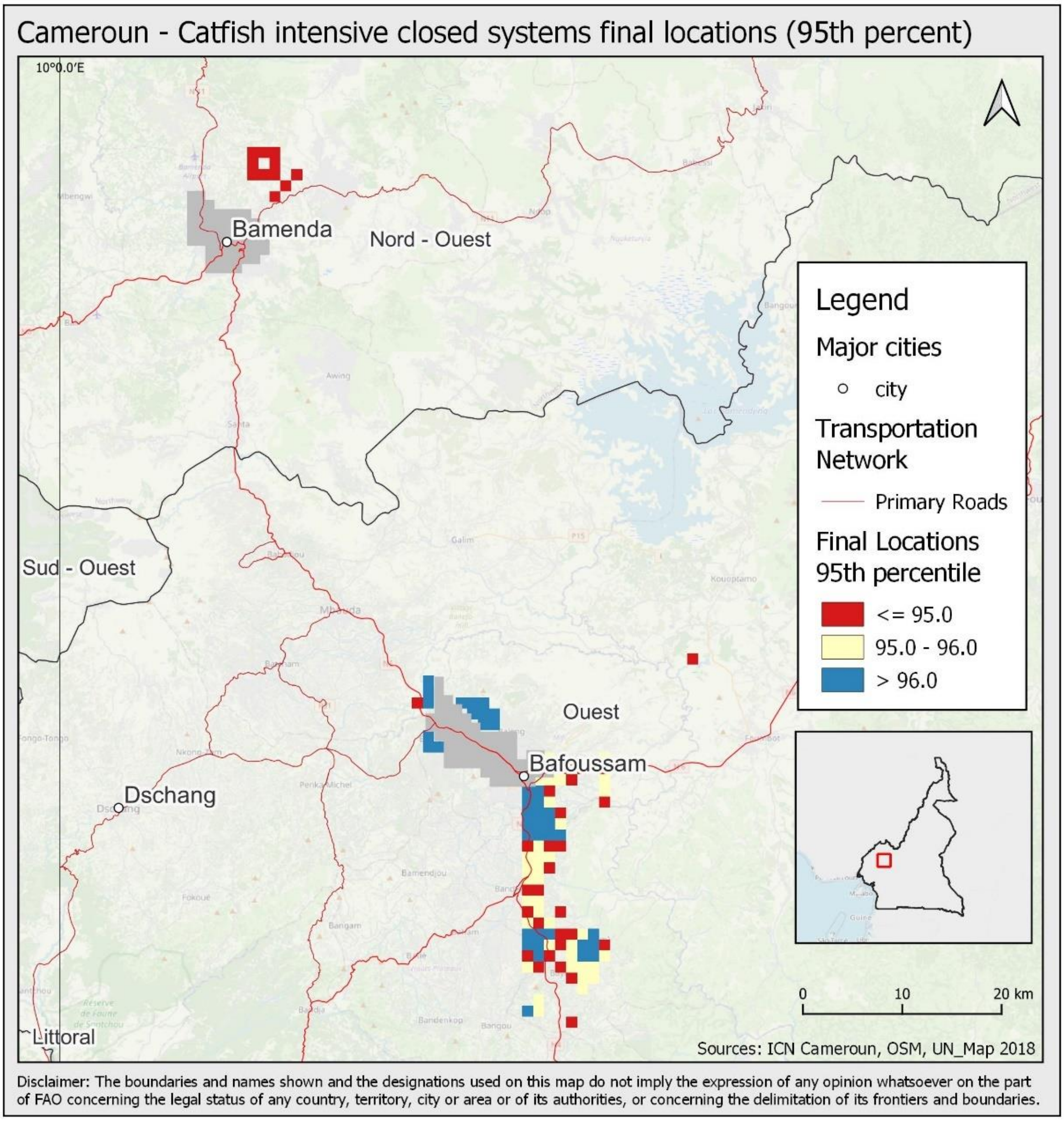

Figure 15 - Bafoussam - Intensive closed systems suitability map – 95th percentile

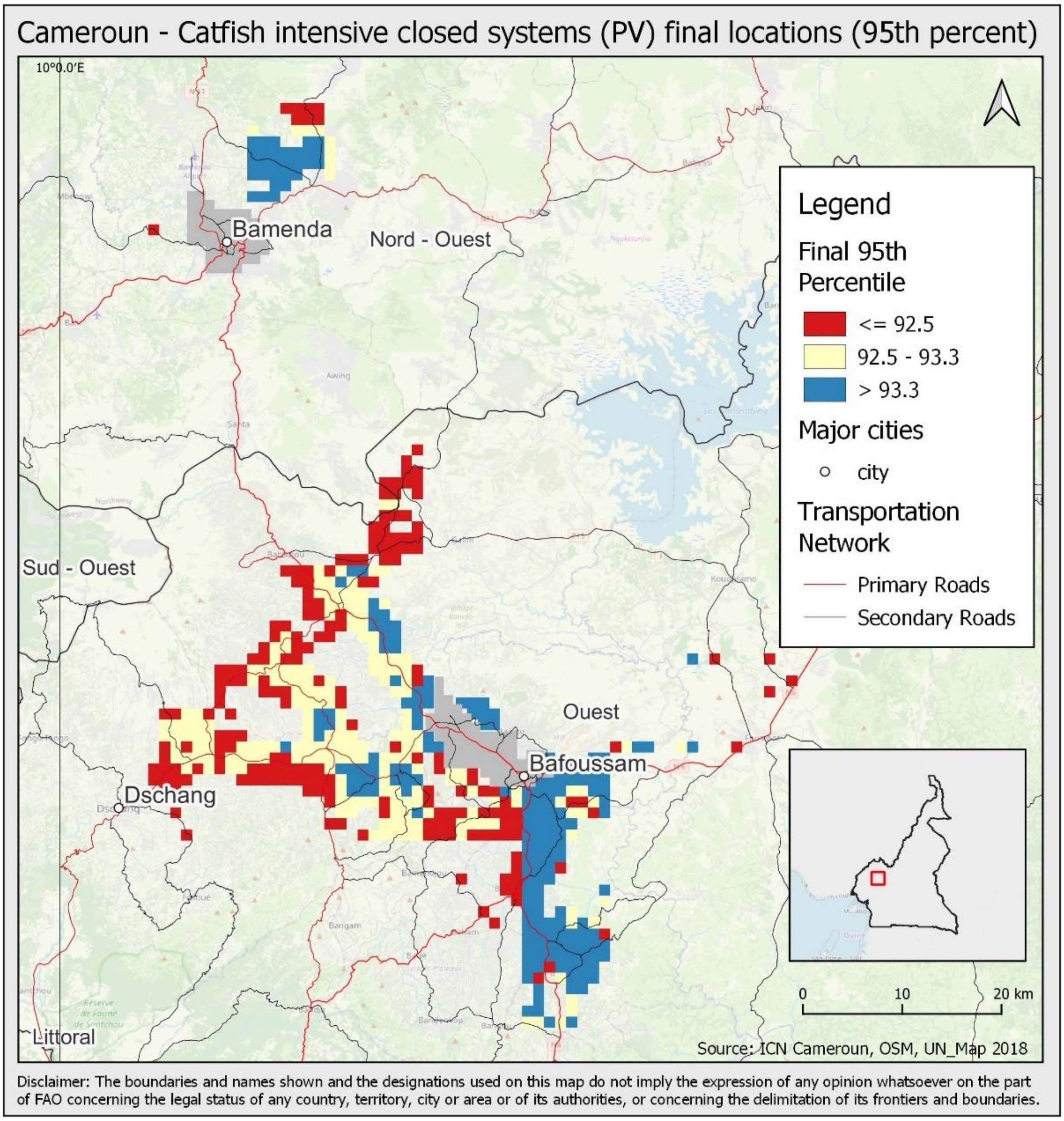

Figure 16 - Bafoussam - Intensive closed systems suitability (PV) map – 95th percentile

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 also 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. Large scale distribution requiring cold chain/storage is obstructed by incipient infrastructure deployment - rural electrification, alternative energy sources and road infrastructure.

Cameroun LWB dataset layer was produced using FAO's waterbodies of Africa, the georeferenced database of dams in Africa and GSW layer seasonality where the seasonality was 12 months [NR1][NR2](maximum).

The modelling methodology differs from the previous analyses since the single defining location factor is the presence of a LWB.

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. Accessibility to ports - considers that high quality/performance tilapia feed is still imported.
e. Tilapia potential yield.

Constraints:

a. Protected areas.

5.3.1 Location Score

The location score is obtained by way of a simple arithmetic weighted sum (normalized/scaled grids). Varying from 0 to 100, with the following weighting: *(“Accessibility MajorUrbanAreas” X 0.40) + (“CropsInput” X 0.15) + (“LivestockInput” X 0.15) + ("Accessibility Ports" X 0.15) + (Tilapia Yield x 0.15)*

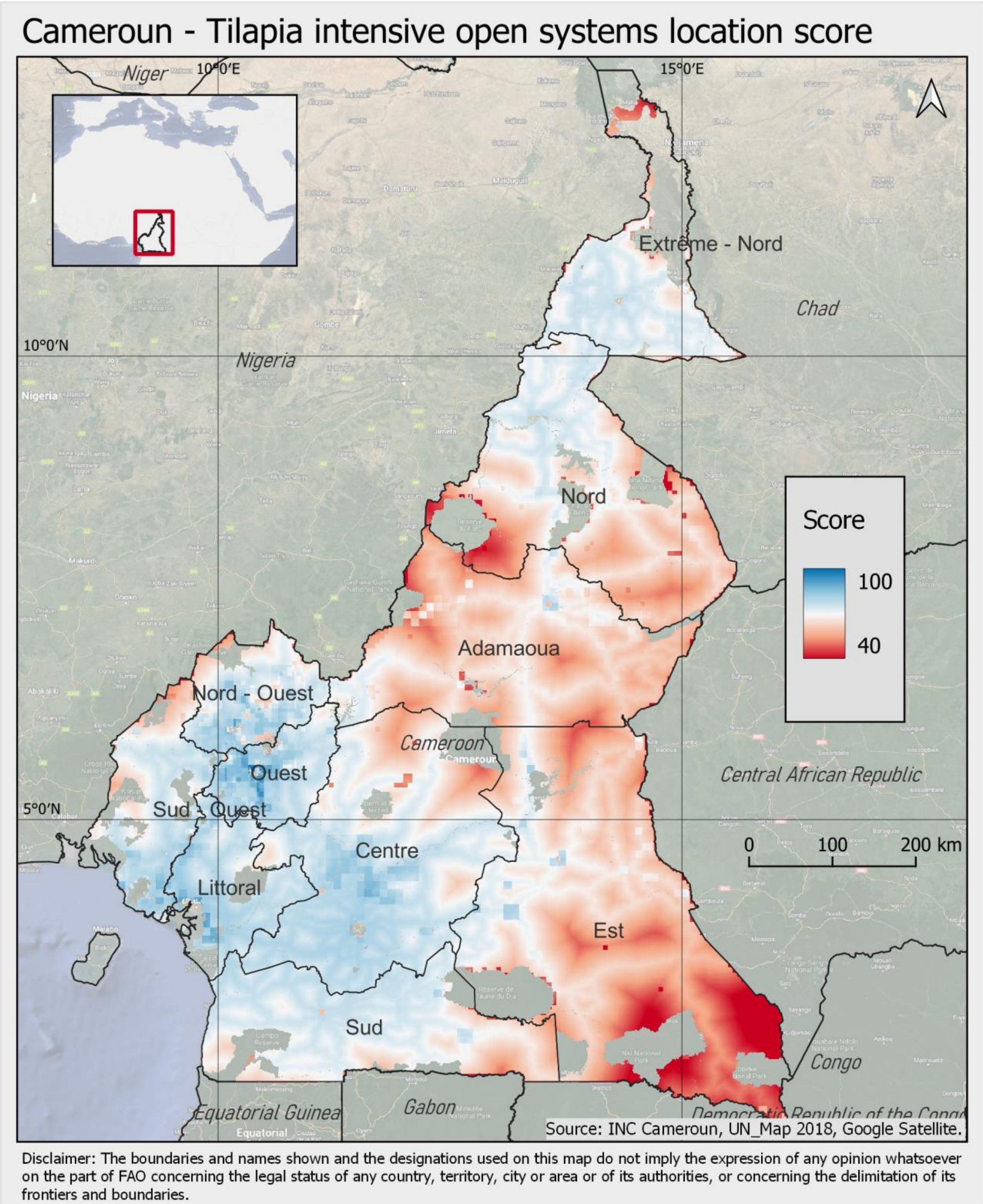

Figure 17 - Tilapia suitability score map

Highest location score areas can be found in *Ouest*, *Nord-Ouest*, *Littoral* and *Centre*.

5.3.2 Constraints and Final Mapping

Recommended locations require the presence of a LWB final mapping follows the approach:

1. ***Clipping*** - Location score mapping is clipped using a LWB 1km buffer polygon layer.
2. ***Zonal statistics tool*** - Extract the maximum (max) score value from the grid layer to the LWB buffer layer polygons.
3. ***LWB Buffer layer symbology*** - set to graduated and classified, using the max value, and equal count (quantile) method with 10 classes.
4. Visual display of the top 2 classes (80th percentile).

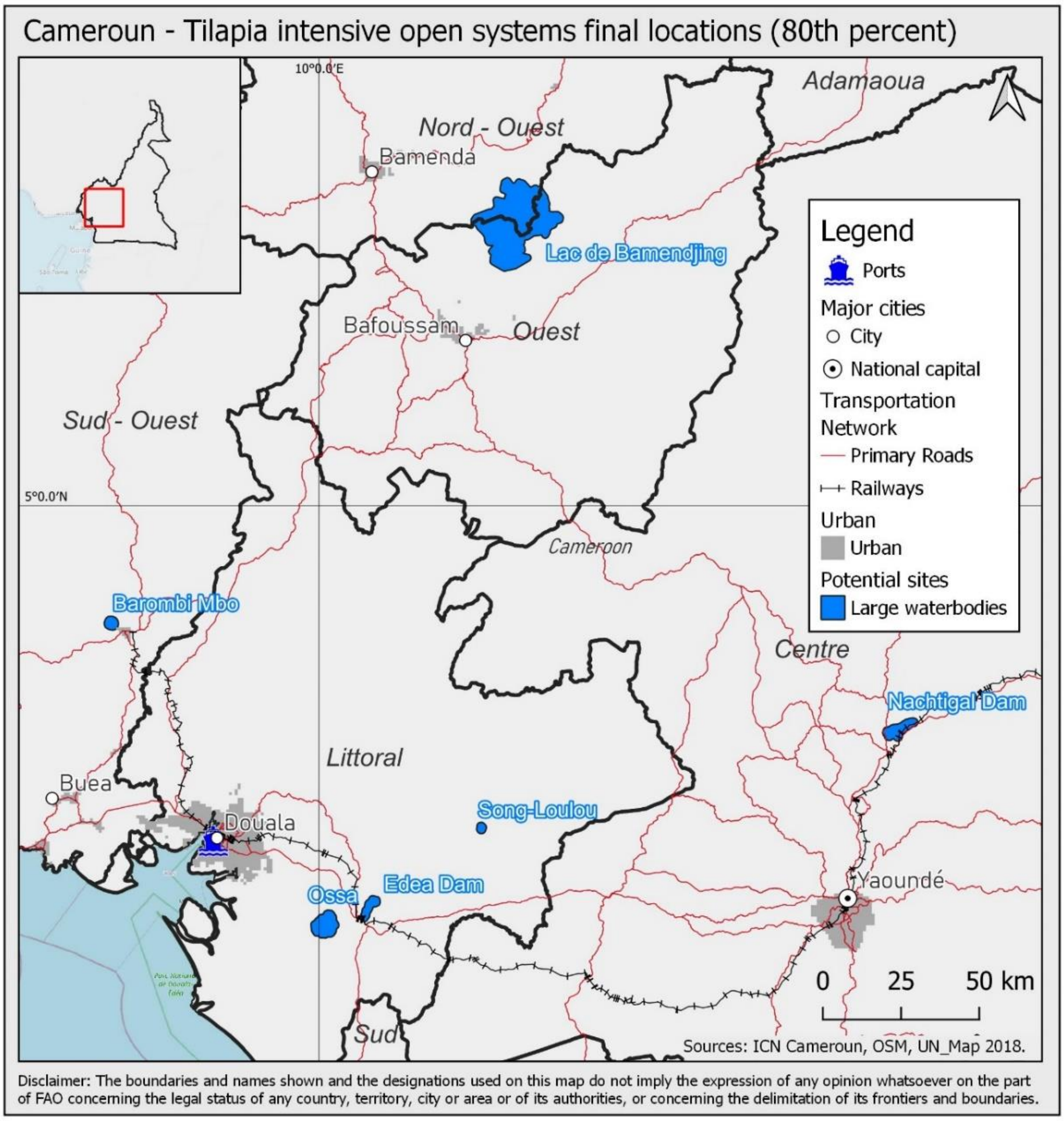

Figure 18 - Potential large water bodies for intensive tilapia farming map (cage/nets)

Top potential sites for Tilapia cage farming appear to be in the proximity of a Douala/Bouea, Yaoundé, Bamenda/Bafoussam triangle:

- Bamendjing Lake – Ouest, Nord-Ouest Regions.
- Barombi Mbo Lake – Sud-Ouest Region.
- Song Loulou dam, Edea dam and Ossa Lake – Littoral Region.
- Natchigal Dam – Centre Region.

CONCLUSIONS

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

With a short coastline and moderately productive maritime area, Cameroun offers extensive inland water resources and good natural conditions for warm-water fish farming. Aquaculture growth has been consistent since 2012, but despite political support and development partners engagement, production has not taken off as expected and a there's a growing seafood trade deficit to meet fish demand.

Infrastructural, financial, and technical aspects constrain the sector development; lack of fish feed industries; low quantity of quality fingerlings; shortage of trained personnel and technical expertise; and difficulties in access to land and finance.
Solutions correspondently point to the need of recycling fish farming techniques; improving farmers organization and participatory planning, easier licensing processes, easier access to inputs; technical support for pond construction, land acquisition and financing. Government intervention on building a favourable environment and providing fundamental infrastructure to support sector growth.
Nigeria's African catfish farming success can set an example to the endeavour. A species highly adapted to local environment, resistant to hi-densities and hard conditions, that can be marketed alive, the cooperative, public/private peri-urban farming model, the "fish farming village" estate.

Departure research questions were formulated as:

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.
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 substantially 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 départments 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 modelling** are developed based on specific theory, thus 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, and intensification potential (PV):

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).
5. *Energy* - Photovoltaic (PV) potential – Intensification potential.

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

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. Water availability is suitable or very suitable for most of the territory.
2. Natural and physical geography criteria are considerably more relevant to open, non-intensive integrated fish/crop farming systems.
3. Intensive systems depend on accessibility to input (feed/seed) and output markets (large urban areas demand).
4. Intensification can take place using closed-circulation technologies: re-circulating tanks, raceways, flow-through systems, and inland ponds, and are reliant on energy supply.

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[9] > 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[10].
2. Demand/market sub-models
    a. Accessibility to large regional cities (markets) - Cross border trade is not considered due to the large fish production consumption deficit.
    b. Urban areas - Population density above 1500 h/k² and area larger than 25 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.

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

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).
    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 limited by absent or unreliable energy distribution networks
    b. Are not dependent on soil characteristics.
    c. Have low dependency on water resources (reuse).
3. Large Water Bodies (LWB) Intensive Tilapia farming systems:
    a. The defining location factor is the presence of a large water body.
    b. High quality/performance feed is imported (accessibility to ports).

CONSTRAINTS

- Protected area constraints as exclusive can be 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
- A ser of assumptions are inherited from in IT access mobile broadband coverage maps estimation.

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.

Mapping is provided at distinct scales for the analysed fish farming systems.

Open non-intensive integrated fish/crop farming systems - ponds or small waterbodies – Highly suitable areas are found in western and coastal areas, but to a certain level also in smaller areas in continental regions where most of the territory has median suitability. A less positive water balance and water seasonality leads to *Nord* and *Extrême-nord* regions to be the less suitable for non-intensive small-scale systems, but low suitability areas can also be found in western regions highlands and in the country southeast.

A Location score filtered using asset wealth index bellow national average classifies large areas of *Sud-Ouest* and *Nord-Ouest* as high score, but smaller areas are also detected in other regions, (*Sud, Littoral, Est,* and *Adamaoua*) that would deserve inspection. Mapping at *Départment* mean values, reveals *Sud-Oest (Manyu, Kupé Manenguba, Ndian, Meme)*, *Littoral* (Moungo) and *Ouest* (Mifi) *départments* with the highest average score and a decreasing pattern from the cost to the interior, with *Nord* and *Extrême-Nord départments* scoring the lowest even tough with low AWI values.

A non-intensive integrated systems priority score is defined by subtracting the normalized AWI to the location score, a high value means a low AWI and high suitability. The measure can be used to prioritize *départments* for interventions, high priority *dèpartments* are: *Sud-Ouest* (Manyu, Kupé

Manenguba, Ndian, Meme) and *Nord-Ouest* (Menchum) *and Est* region (Haut–Nyong, Kadeï, Boumba-Et-Ngoko).

Intensive closed farming systems adoption is limited by electricity distribution networks. Closed/semi-closed-circulation technologies (re-circulating tanks, raceways, flow-through systems, and ponds) are considerably 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.

Intensive closed commercial farming systems suitability spatial pattern centres on output markets, large metropolitan/urban, since the demand factor is of major importance. *Littoral* Douala, Centre Yaoundé, *Ouest* and *Nord-Ouest* Bafoussam/Bamenda, Garoua *Nord*, and Maroua *Extrême-Nord*.

Using the PV potential as an intensification measure classifies coastal areas with lower scores but doesn't change the previously identified pattern. Final maps identify most suitable peri-urban areas around major urban regions in the country, Youndé, Douala, Bafoussam/Bamenda at a smaller scale (using a broader 90th percentile) Maroua (*Extrême-Nord*). It must be stressed that farmgate sales and market sub-models considers solely the population density dimension and not poverty or purchasing/acquisitive power.

The tilapia open intensive systems in LWB using open-net pens/ cage techniques, are considered one of the most profitable, but with downsides from exchanges with the surrounding environment.

Zoning differs from other models since the defining factor is the presence of a LWB.

Highest location score areas can be found in *Ouest*, *Nord-Ouest*, *Littoral* and *Centre*. Top potential sites for Tilapia cage farming appear to be in the proximity of a Douala/Bouea, Yaoundé, Bamenda/Bafoussam triangle:

- Bamendjing Lake – *Ouest*, *Nord-Ouest* Regions.
- Barombi Mbo Lake – *Sud-Ouest* Region.
- Song Loulou dam, Edea dam and Ossa Lake – *Littoral* Region.
- Natchigal dam – *Centre* Region.

RECOMMENDATIONS

Caution and examination should be considered over intensification and growth within aquaculture development, as well as sustainability and possible impacts. Environment, health and disease, and land and water competition challenges must be assessed, and objective assessment of ethnic, cultural, religious, socio-political diversity, and conflict issues should frame interventions.

Environmental issues are missing from the equation for most of the industry literature. Integrated farming systems can positively impact sustainability and recirculation techniques have low water requirement and output effluents. Fish farming can also reduce fishing pressure. Still, little research and data are available on impact issues 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.

There is evidence of an increase in harmful organic and chemical effluents, and direct discharge of untreated waste waters in river streams (Albine et al., 2021; Bouelet Ntsama et al., 2018). Open systems exchange with the surrounding environment, transferring waste, chemicals, parasites, disease and have a high potential for fish escapes.

Health and disease monitoring and management must also be considered, putting in place surveys, monitoring, diagnostic, and guidelines on biosecurity.

Activity expansion and impacts additionally increase land and water competition. Those are already prone to conflict problems. Open systems in public waters commonly face conflicting interests.

This set of long-term impacting issues must be balanced with the immediate socio-economic objectives and improving productivity should promote environmentally sustainable production and extension technologies.

Besides considering physical geographical conditions, supply, demand, infrastructure, accessibility, and alternative energy (photovoltaic potential), awareness of social-cultural, ethnic, and political context and factors must guide proposed interventions. A holistic approach can result in successful and sustainable adapted proposals, targeting 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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