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[Nelson Ribeiro Filho](#) *

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Article

A Geographic Information System Multi-Criteria Evaluation Assessment of Freshwater Aquaculture Suitability in Benin

Nelson Ribeiro Filho

Food and Agriculture Organization of the United Nations (FAO), Digital FAO and Agro-Informatics Division (CSI); nelson.rosasribeirofilho@fao.org

Abstract

This paper translates a GIS-based multi-criteria evaluation (GIS-MCE) developed for the Food and Agriculture Organization (FAO) Hand-in-Hand Initiative (HiH), into a scientific manuscript on aquaculture zoning and site suitability in the Republic of Benin. We integrate sub-models on market accessibility, demand (population and asset wealth index), biophysical conditions (water balance, soils, slope), and input availability (crop and livestock systems) to produce suitability indices for three fish farming systems: (i) extensive to semi-intensive small-scale and integrated ponds; (ii) peri-urban intensive closed systems (tanks, ponds, RAS); and (iii) intensive open tilapia cages in waterbodies. A marked south–north gradient emerges, with southern and central communes showing highest suitability for non-intensive systems. Priority communes include Bassila, Bantè, Ouessè, Savè, Kétou, Djidja, Agbangnizoun, Zangnanado, Ouinhi, Lalo, Bonou, and Adjohoun. Intensive closed systems concentrate around Abomey-Calavi, Cotonou, and Porto-Novo due to superior market access. For open cage farming, southern permanent waterbodies—particularly Lakes Ahémé and Nokoué and selected reservoirs such as Zagnanando, Azili, and Ilauko—appear promising, though environmental risks (eutrophication, pollution) warrant caution. We discuss methodological assumptions, data constraints, and limitations (e.g., absence of formal MCDA methods), and conclude with policy recommendations emphasizing environmental safeguards, support to traditional systems (e.g., *whédo*), improved feed and seed access, and strengthened biosecurity and monitoring frameworks for sustainable aquaculture expansion.

Keywords: GIS-MCE; aquaculture zoning; Benin; tilapia; integrated aquaculture–agriculture; site suitability; accessibility

1. Introduction

Global demand for aquatic foods is rising even as capture fisheries face constraints from overfishing, climate variability, and environmental degradation, positioning aquaculture as a critical pathway to improve food security, nutrition, and livelihoods in low- and middle-income countries [1,2]. In Sub-Saharan Africa, aquaculture growth has outpaced the global average but still accounts for a modest share of supply, with production concentrated in a few countries and hindered by persistent bottlenecks in inputs, finance, and governance [3,4]. Within this context, spatially explicit, evidence-based planning is needed to guide public investment and de-risk private capital while aligning aquaculture development with social and environmental objectives.

Geographical Information Systems–Multicriteria Evaluation (GIS-MCE) provides a rigorous, transparent framework for integrating heterogeneous criteria and stakeholder preferences into reproducible suitability surfaces for land- and water-use planning [5–9]. Foundational continental analyses have shown how biophysical and market factors can be combined via sub-models and decision rules to identify promising aquaculture zones in Africa, offering a transferable template for national-scale assessments[10]. Yet, key debates persist: results are sensitive to data quality, criteria

selection, and weights; different, defensible specifications can yield different priorities; and claims about environmental and social impacts are unevenly evidenced across contexts. In parallel, policy and investment narratives often privilege intensive commercial models (e.g., cages or recirculating systems) over smallholder, integrated systems that may deliver broader nutrition and poverty-reduction benefits but face structural barriers to inputs, finance, and services [11–13].

Benin exemplifies these challenges and opportunities. The fisheries and aquaculture sector contributes to GDP and agricultural employment, yet domestic supply remains insufficient and imports are rising amid stagnating capture production [14,15]. Despite growing policy support—particularly for cage culture in southern hydrographic systems—producers commonly report constraints including the cost and availability of quality fry and feed, limited access to credit, and weak cold-chain and electricity infrastructure [15,16]. At the same time, culturally embedded systems such as the seasonal *Whédo* ponds illustrate the potential of locally adapted practices to support diverse species and household income, yet it remains under-recognized in policy discourse [17–19].

Purpose and Significance

This study develops and applies a system-specific GIS-MCE framework to delineate aquaculture suitability in Benin across complementary development objectives. We (i) identify districts and departments where extensive to semi-intensive, small-scale integrated freshwater systems are most likely to contribute to poverty alleviation, improved nutrition, and food security; and (ii) locate high-return opportunity areas for intensive commercial closed (recirculating/flow-through/pond) and open cage fish farming systems. Building on established approaches, we update criteria, weights, and constraints to reflect current sector realities, spanning biophysical conditions (water balance and seasonality, soils, terrain, wind/temperature–yield), supply (crop by-products for feed; livestock densities), demand (population density, metropolitan markets, asset wealth), and infrastructure/accessibility via raster-based travel-time modelling [20,21]. For closed intensive systems, we additionally incorporate proximity to major roads, access to finance, and mobile broadband coverage as operational prerequisites.

Main aim and Principal Conclusions

Our aim is to generate transparent, reproducible, decision-ready suitability maps that distinguish where different fish farming systems are most likely to succeed under prevailing constraints. More broadly, results are sensitive to data quality, criteria selection, and weighting; alternative, defensible specifications can yield different spatial priorities [6,7,22,23]. A reflexive stance is warranted because data and modelling choices are not neutral [24,25]. Evidence on environmental and social impacts varies by system and context. Collectively, these contributions provide a structured basis for aquaculture zoning in Benin and a portable template for similar assessments across Sub-Saharan Africa [5,10].

2. Materials and Methods

Study Area and Scope

We mapped aquaculture suitability for Benin, with separate models for (i) small-scale extensive to semi-intensive pond and integrated systems, (ii) peri-urban intensive closed (semi-closed) systems (ponds, tanks, RAS, flow-through/recirculation), and (iii) intensive tilapia cage systems in open waterbodies. Analyses focused on African catfish and Nile tilapia and targeted both poverty-alleviating smallholder systems and high-ROI commercial operations.

Overall Modelling Framework

We adapted a raster-based multi-criteria evaluation (MCE) framework that integrates constraints (exclusive criteria), biophysical factors (water, soils, slope), inputs (crops, livestock), market access (population density, accessibility, asset wealth), and —where relevant— potential yield. We revised sub-models, criteria, weights, and constraints to reflect current data availability, contemporary production systems, and higher-resolution disaggregation.

Data and Sources

We compiled, harmonized, and processed all layers in a single projected, meter-based CRS. Each dataset was clipped to Benin’s national boundary prior to analysis. Publicly accessible datasets include:

- Legacy FAO aquaculture layers (soil suitability and potential yields).
- WaPOR v4 (2018–2023) precipitation (PCP) and reference evapotranspiration (RET).
- JRC Global Surface Water (Seasonality & Extent, 1984–2021).
- IFPRI MAPSPAM 2017 (Global Spatially-Disaggregated Crop Production Statistics).
- GLW4—Gridded Livestock of the World (goats, sheep, pigs, cattle, chickens, ducks).
- OpenStreetMap (OSM) roads/railways/places/POIs (Geofabrik Africa extracts).

Restricted-access datasets include: AtlasAI (population density and Asset Wealth Index) and GSMA Collins Bartholomew Mobile Coverage Explorer (broadband cellular coverage). Access requires institutional or commercial agreements; redistribution is restricted.

Pre-processing and Database Construction

All vector layers were selected/edited by location and attribute and stored in a country-level GeoPackage. OSM features were filtered into function-specific layers using the fclass attribute, including major_roads (primary, primary_link, trunk, trunk_link), secondary_roads (secondary), tertiary_roads (tertiary), local_roads (residential, unclassified), tracks (track, service, track_grade3/4/5), and walk (pedestrian, footway, path, living_street, steps). Railways were selected by location; bank agencies were extracted from OSM POIs where fclass = bank. Urban places were selected from OSM places with fclass in {city, town, national_capital}.

All transportation network and hydrographic vectors, plus land and water surfaces, were rasterized to a common grid for cost-distance modelling. All criteria rasters were min–max normalized to [0,100]; unless stated otherwise, 0 indicates least suitable (or highest travel cost) and 100 indicates most suitable (or lowest cost).

Accessibility Modelling (Travel Time/Cost Surfaces)

Assumptions: (i) Major urban areas are contiguous $\geq 25\text{ km}^2$ with population density $>1,500$ persons/ km^2 , to which accessibility is computed; (ii) water surfaces are polygonal; (iii) transport networks are linear; (iv) road network conditions are poor; (v) lakes/rivers are treated as navigable surfaces (small–medium cargo craft) without explicit port infrastructure. Navigable waterways derive from OSM water/waterway layers.

Assumed speeds for the multimodal cost surface are listed in Table 1.

Table 1.

Network class	Assumed speed (km·h ⁻¹)
Primary roads	50
Secondary roads	40
Tertiary roads	35.3
Local roads	25
Tracks	10

Walk	5
Off-network land	3
Waterways	10
Railways	60
Open water	20

We overlaid all mode-specific grids to create a friction surface by propagating the minimum cell time (i.e., maximum effective speed). Cumulative cost-distance (minutes) to major urban places (Bohicon, Cotonou, Porto-Novo, Parakou) was computed and then min-max scaled to [0,100].

Market/Demand Sub-Model — Population-Weighted AWI Accessibility

This subsection refines the weighted-accessibility-to-urban-areas method by explicitly defining the population-wealth weighting, and implementation details for multi-city accumulation and normalization. It is consistent with the GIS-MCE framework applied across agrifood systems and with the accessibility sub-model built from raster-based cost surfaces.

Data Inputs

- Urban polygons: delineated from population density > 1,500 persons·km⁻² and contiguous area ≥ 25 km² (thresholds may be tuned to country and value-chain context). Urban places (targets) are OSM places with fclass ∈ {city, town, national_capital} intersecting urban polygons.
- Population: AtlasAI population density raster aggregated by urban polygons using zonal statistics (sum of people per polygon).
- Asset Wealth Index (AWI): AtlasAI AWI raster summarized by urban polygons (mean), then normalized to positive values prior to weighting.
- Accessibility rasters: cumulative travel time/cost surfaces computed to each target urban place using the multimodal friction surface (roads, rail, waterways, land/walk; speeds as per Table 1 of Methods).

Method Steps

- 1) Zonal statistics — population totals: For each urban polygon i, compute POP_i = Σ(population raster) within i.
- 2) AWI normalization: Compute AWI_i from zonal mean and rescale to AWI_i⁺ ∈ [0,1] (strictly positive). If AWI contains negatives/zeros, apply a shift to ensure positivity before min-max scaling.
- 3) Market share weights: Define market pull weights as

$$w_i = (POP_i \times AWI_i^+) / \sum_j (POP_j \times AWI_j^+).$$

- 4) Per-city accessibility: Build per-target accessibility rasters A_i(x) (scaled to [0,100], where higher is better).
- 5) Composite demand surface: Combine per-city rasters with weights using a weighted sum
$$D(x) = \sum_i [w_i \times A_i(x)].$$
- 6) Standardization: If needed, re-normalize D(x) to [0,100] to integrate with other criteria in the MCDA.

Optional Variants and Extensions

- Regional demand and trade: Augment targets with cross-border regional capitals; compute weights as above and include their per-city accessibility rasters to capture export or import-substitution strategies.

- Port accessibility: For tradable commodities/systems sensitive to import/export logistics, include maritime ports as additional targets with their own accessibility rasters and, if desired, weights based on throughput proxies.
- Threshold tuning: Adjust the $1,500 \text{ persons} \cdot \text{km}^{-2}$ and $\geq 25 \text{ km}^2$ thresholds to reflect national urban hierarchy and the scale of the production/processing system.
- Sensitivity analysis: Evaluate robustness by perturbing thresholds and re-weighting AWI vs. population to inspect the effect on $D(x)$ percentiles and short lists of priority sites.

Implementation Notes (QGIS/GRASS/GDAL)

- Perform zonal statistics (population sum; AWI mean) on the urban polygons; compute weights externally (field calculator) or via attribute joins.
- Generate $A_i(x)$ per target using cumulative cost-distance on the multimodal friction surface; rescale to $[0,100]$.
- Create $D(x)$ by stacking $A_i(x)$ and applying the weights with GRASS r.series (weighted sum) or raster calculator.
- Document the exact list of targets used (city names/IDs) and the final weights w_i to ensure reproducibility.

Edge Cases and Data Quality

- Where multiple contiguous urban polygons represent a single metropolitan area, dissolve prior to zonal statistics to avoid double counting.
- If AWI variance is small within urban polygons, consider smoothing or quantile normalization prior to weighting.
- For cities with limited or no road/rail connectivity (isolation), ensure water/land walking modes are present so $A_i(x)$ is defined nationwide.

Biophysical Sub-Models

Water

We modelled water via annual water balance and surface water persistence. Water balance used WaPOR v4 PCP and RET (2018–2023): clip $\rightarrow$ r.series mean $\rightarrow$ resample to common grid $\rightarrow$ $(PCP \times 1.1) - (RET \times 1.3) \rightarrow$ scale to $[0,100]$. GSW Seasonality = 12 polygons represented permanent water (criterion for cage farming), and GSW Extent polygons defined flood-prone masks for non-intensive ponds.

Soils and Terrain (Pond Construction)

FAO soil suitability variables (acid sulfate, organics, lime requirement, clay, water-table depth, salinity/alkalinity, gypsum, soil depth) were clipped and scaled to $[0,100]$. Slope (degrees) from a 30" DEM was masked to $< 8^\circ$ and inverse-normalized so that $0 = 8^\circ$ (unsuitable) and $100 = 0^\circ$ (flat/optimal). Soils and slope were combined for ponds as $\text{SoilSlope} = (1.5 \times \text{norm_soils} + \text{SlopeSuit}) / 2.5$. Intensive closed systems use slope separately.

Input Sub-Models

Crops

Aggregate crop production (MAPSPAM 2017) was clipped to Benin and scaled to $[0,100]$; it proxies local availability of feed ingredients and crop by-products.

Livestock

Two inputs were built: (1) non-intensive/integrated systems—chicken + duck densities aggregated (sum) and scaled to [0,100]; (2) intensive systems—weighted sum by average live weight: $0.089 \times \text{goat} + 0.089 \times \text{sheep} + 0.626 \times \text{cattle} + 0.188 \times \text{pig} + 0.007 \times (\text{chicken} + \text{duck})$, then scaled to [0,100].

Suitability Modelling and Constraints

(A) Small-Scale Extensive to Semi-Intensive & Integrated Ponds

Assumption: water availability is generally adequate; therefore, water is down-weighted relative to market-proximal factors. Criteria (all scaled to [0,100]): WaterBalance; SoilSlope; By-products ($1.5 \times \text{ChickenDuck} + \text{CropAgg}$); FarmGateSales.

Suitability index: $0.50 \times \text{WaterBalance} + 0.25 \times \text{SoilSlope} + 0.125 \times \text{ByProducts} + 0.125 \times \text{FarmGateSales}$. Commune-level zonal statistics yielded mean suitability and a priority index defined as (normalized, population-weighted mean AWI – mean suitability) to emphasize low-wealth/high-suitability areas.

(B) Peri-Urban Intensive Closed (Semi-Closed) Systems

Rationale and assumptions: closed systems (ponds/tanks/RAS/flow-through) are less constrained by soils and climate, require limited water through reuse/recirculation, and are primarily market-driven. Criteria: WeightedAccessibility(Major Urban Areas), WaterBalance, Crops, Livestock, Slope.

Index formula: $0.50 \times \text{WeightedAccessibility} + 0.20 \times \text{WaterBalance} + 0.10 \times \text{Crops} + 0.10 \times \text{Livestock} + 0.10 \times \text{Slope}$. Constraints: exclude dense urban areas ($>1,500$ persons·km⁻² and >25 km²), permanent waters, and flood-prone areas. Exclusive siting rules: within 2 km of major roads, within 20 km of bank agencies, and with mobile broadband coverage. Final selection: retain pixels in the top 70th percentile (dense urban cores excluded).

(C) Intensive Open Tilapia Cages in Waterbodies

Criteria: presence of permanent waterbodies (Seasonality = 12), WeightedAccessibility(Major Urban Areas), Crops, and Livestock; potential yield (temperature) was non-differentiating and omitted. Suitability: $0.50 \times \text{WeightedAccessibility} + 0.25 \times \text{Crops} + 0.25 \times \text{Livestock}$.

Constraints & site selection: buffer permanent water polygons by 2 km, clip suitability by this mask, compute per-polygon maximum suitability (zonal statistics), and display/select ≥ 70 th percentile values to indicate priority waterbodies. Contextual environmental constraints (eutrophication/pollution) should be assessed at feasibility stage.

Table 2. summarizes criterion weights by production system.

System	Criterion	Weight
Extensive/semi-intensive & integrated ponds	WaterBalance	0.50
	SoilSlope	0.25
	ByProducts	0.125
	FarmGateSales	0.125
Intensive closed (semi-closed)	WeightedAccessibility	0.50
	WaterBalance	0.20
	Crops	0.10
	Livestock	0.10
	Slope	0.10
Open tilapia cages	WeightedAccessibility	0.50
	Crops	0.25
	Livestock	0.25

Key thresholds and buffers used in the analysis are summarized in Table 3.

Table 3.

Parameter	Value/Rule
Urban density threshold	Population density > 1,500 persons·km ⁻² AND area ≥ 25 km ²
Slope feasibility for ponds	< 8° (inverse-normalized; 0 = 8°, 100 = 0°)
Road proximity (intensive closed)	≤ 2 km from major roads
Bank proximity (intensive closed)	≤ 20 km from bank agencies
Waterbody buffer (open cages)	2 km buffer around permanent waters (Seasonality = 12)
Normalization	Min-max to [0,100] for all continuous criteria

Software, Parameters, and Reproducibility: All geospatial processing, sub-model construction, and suitability/index calculations were executed through a reproducible, script-based workflow developed in the QGIS Python Console and the integrated code editor. The scripts orchestrate data ingestion (when feasible), preprocessing (clipping, reprojection, resampling, rasterization), normalization, application of constraints/masks, and weighted combinations used to generate the suitability indices and zonal statistics.

QGIS 3.40.12 (“Bratislava”) served as the primary execution environment. The QGIS Processing framework was used both to run core algorithms and to accelerate script development by capturing model steps via the Processing History/log, which was then translated into Python workflows and complemented with additional Python packages. Raster operations relied on GDAL 3.11.5 (“Eganville”) (e.g., slope derivation), and GRASS GIS 8.4.1 was invoked via the QGIS GRASS provider for selected raster analyses (e.g., r.series).

Where applicable, source layers were acquired programmatically (including automated extraction of WaPOR layers via web/API-based download mechanisms) and then harmonized into a single projected, meter-based CRS. Vector-to-raster conversion and raster processing were performed on a common grid (cell size: 1 km) to ensure alignment. Continuous criteria were normalized to [0,100] after clipping to national boundaries. Thresholds, buffers, and exclusion masks (urban extent, flood-prone areas, permanent water, slope limits) followed the values reported in Tables 1–3.

Final cartographic products (map layouts and figure exports) were produced manually in QGIS Layout Manager from the scripted outputs to ensure consistent symbology, labeling, and publication-quality formatting.

Environment summary: QGIS: 3.40.12 “Bratislava”; GDAL / osgeo: 3.11.5 “Eganville”; Key Python packages: numpy 1.26.4, rasterio 1.4.3, fiona 1.10.1, shapely 2.0.6, requests 2.32.4, PyQt5 5.15.11, bs4 4.12.3.

Code, Data, and Materials Availability: Processing code/scripts are not publicly available due to organizational intellectual property policies. The analysis was implemented as a set of QGIS/Python scripts (Python Console + code editor) that automate data ingestion (including programmatic downloads for selected layers), preprocessing, sub-model generation, and suitability/index calculations using QGIS Processing, GDAL and GRASS providers. To facilitate replication, we provide complete algorithmic descriptions, parameter values, thresholds, weights, data sources, and step-by-step workflows in this section and Tables 1–3. Derived outputs (suitability rasters, zoning layers, and administrative-unit summary tables) are publicly available via the FAO AgroInformatics Platform and the FAO Data Catalogue under CC BY 4.0 unless otherwise indicated in the dataset metadata (see Data Availability Statement).

Ethical Approval: This study involves no human or animal interventions and did not require ethics approval.

Use of Generative AI: Use of Generative AI: Microsoft Copilot (M365 Copilot) was used to improve clarity and consistency of the manuscript, including restructuring and standardizing pre-existing technical reports into a journal-compliant Materials and Methods section, and to support scripting, troubleshooting, and debugging during development of the QGIS/Python processing workflow. No new analyses, datasets, or figures were generated by AI; all scientific content (datasets, parameters, workflows, weights, and formulas) originates from the author and cited sources. The author reviewed, validated, and edited all AI-assisted outputs and takes full responsibility for the final content.

3. Results

This section reports the spatial suitability outputs and priority areas for three aquaculture system types—(i) extensive/semi-intensive (including integrated systems), (ii) peri-urban intensive closed (semi-closed) systems, and (iii) open intensive tilapia cage systems—followed by concise interpretations and actionable conclusions for site selection.

3.1. Extensive/Semi-Intensive Systems

3.1.1. Suitability Index

The suitability index exhibits a clear north–south gradient. Most of the southern regions are highly suitable, whereas the extreme north and northwest tend to be less suitable; only a few southern areas fall into mid-range suitability. Commune-level averages confirm broad national suitability with exceptions in a handful of communes in the far north and northwest (see Figures 1–3).

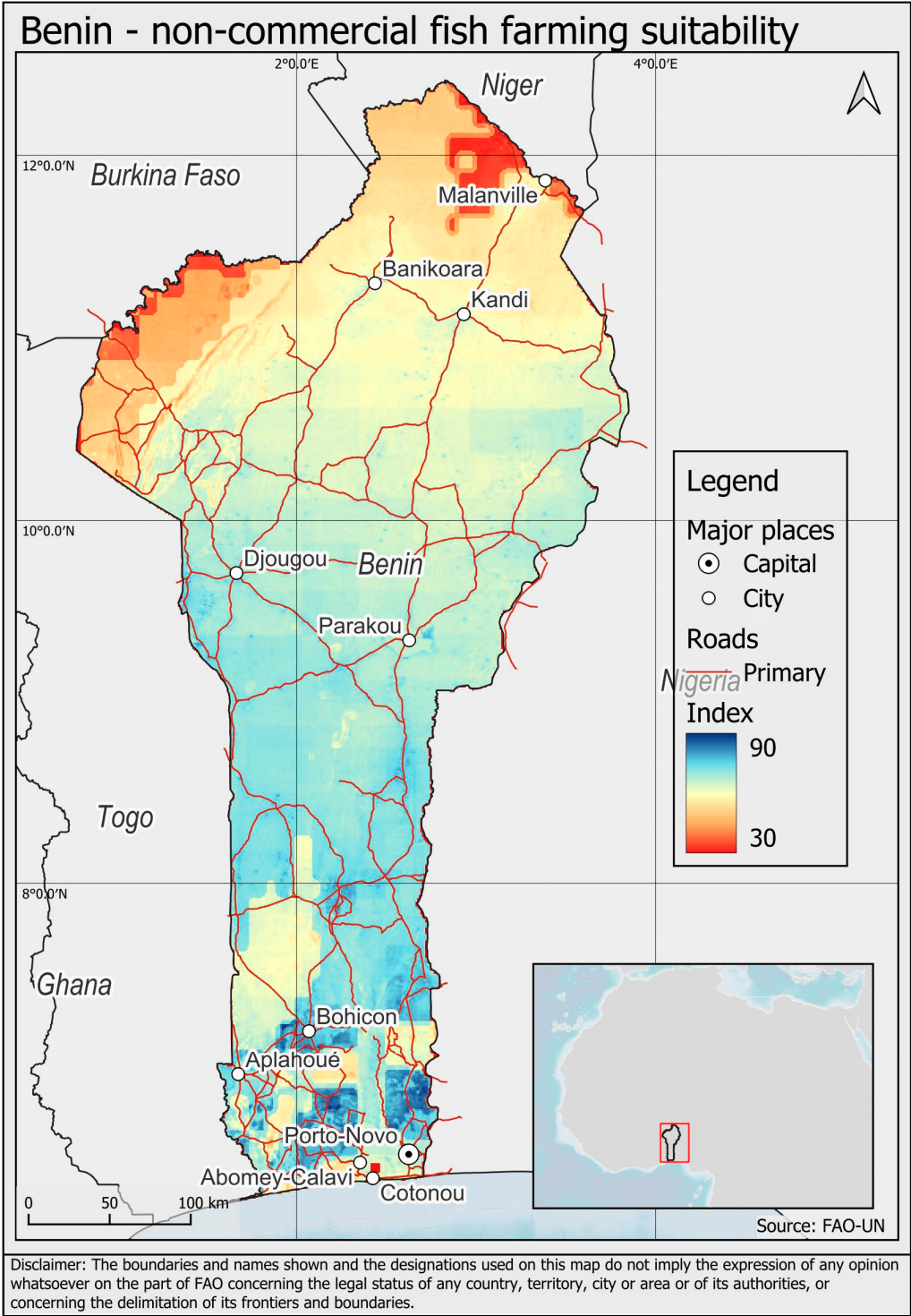


Figure 1. Non-intensive and integrated systems suitability index.

At the Commune level, the average suitability index also indicates that most of the country is suitable to very suitable, except for a few Communes in the extreme north and northwest, where the mean suitability index falls within the mid-range.

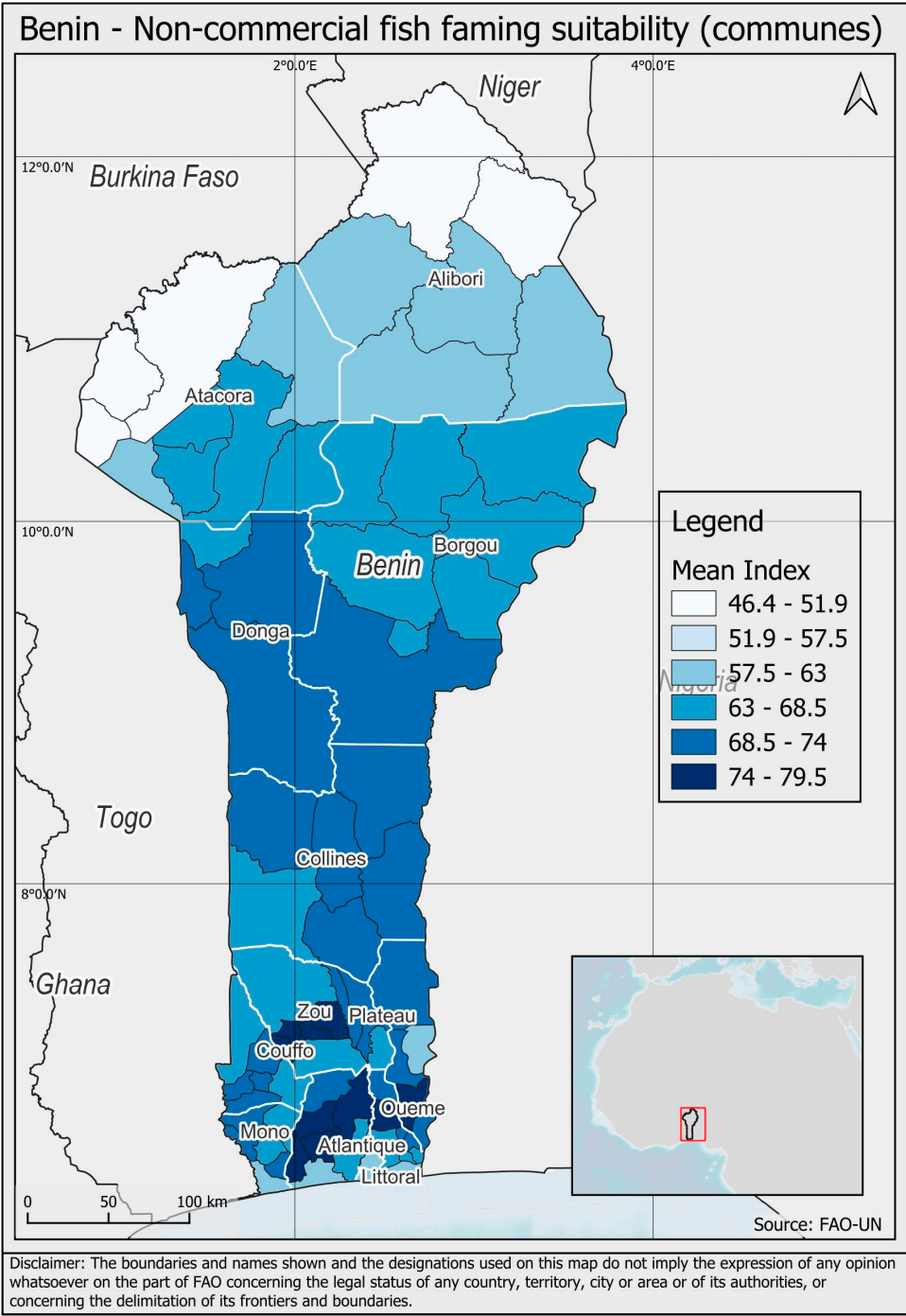


Figure 2. District average non-intensive systems suitability index.

Communes with the highest average suitability include:

- Zou Province: Agbangnizoun, Abomey, Bohicon, Za-Kpota
- Atlantique: Zé, Allada, Tori-Bossito, Kpomassè
- Ouémé: Adjohoun
- Plateau: Sakété

In the central region, most areas fall in the 68.5–74 class, notably Collines and Donga provinces and Tchaourou (southern Borgou).

3.1.2. Priority Mapping for Interventions

A Commune Priority Index (difference between normalized AWI and mean suitability) highlights where high suitability coincides with lower wealth indicators. Higher values indicate

Communes where interventions have greater potential impact on poverty reduction, food security, and malnutrition.

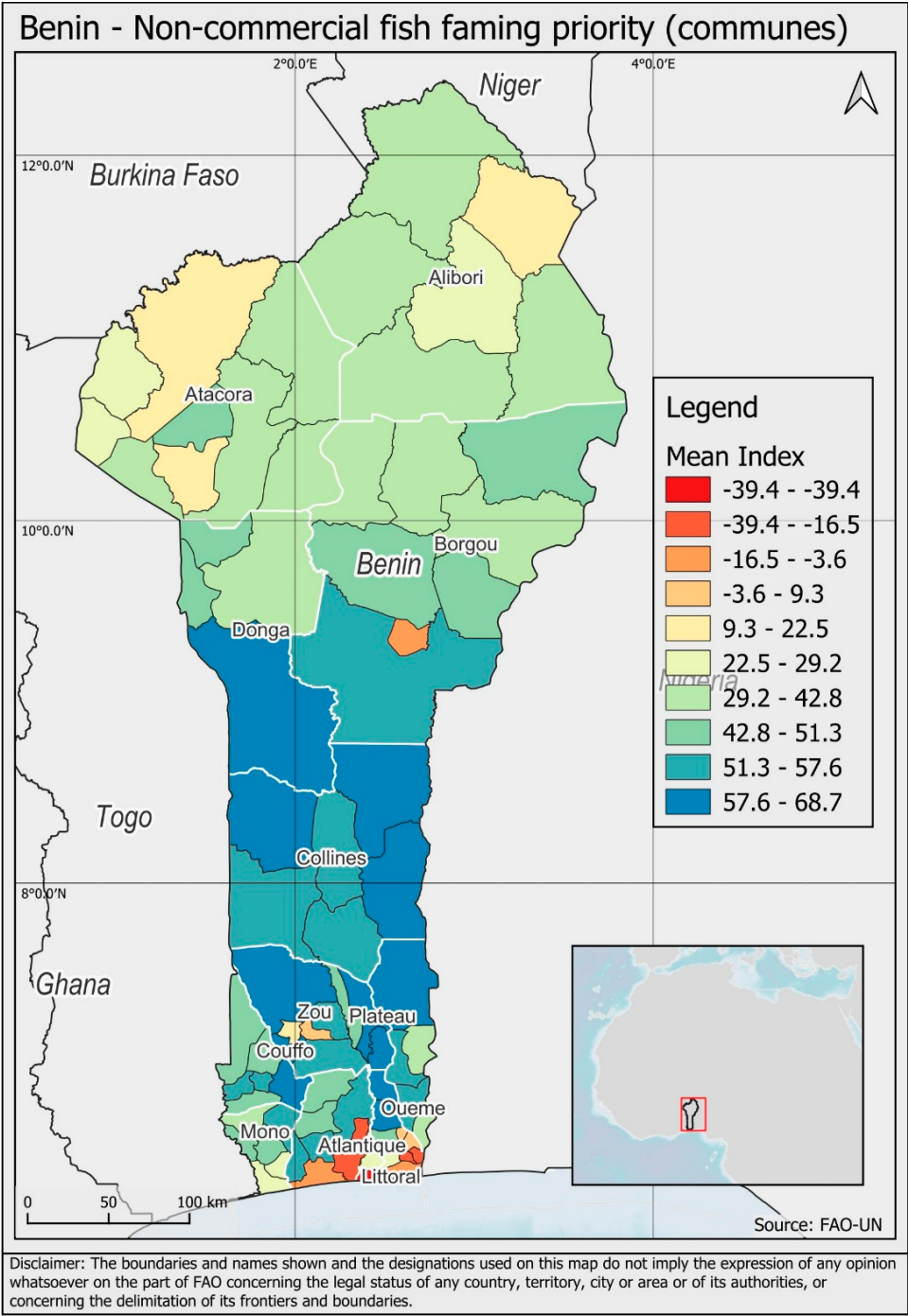


Figure 3. Commune priority—non-intensive systems.

Highest-priority communes (central/southern):

- Donga: Bassila
- Collines: Bantè, Ouessè, Savè
- Plateau: Kétou
- Zou: Djidja, Agbangnizoun, Zangnanado/Ouinhi
- Couffo: Lalo
- Ouémé: Bonou, Adjohoun

Lowest-priority communes (urbanized/higher wealth):

- Parakou (Borgou); Abomey and Bohicon (Zou); Ouidah and Abomey-Calavi (Atlantique); Sèmè-Podji, Porto-Novo, Adjarra, Avrankou, Akpro-Missérété (Ouémé); and some far northern/northwestern communes such as Malanville (Alibori) and Tanguiéta (Atacora).

3.2. Peri-Urban Intensive Closed (Semi-Closed) Systems

3.2.1. Suitability Index

For intensive closed systems (ponds, tanks, RAS, flow-through), market accessibility is the dominant factor (50% weight). High suitability clusters around major urban centres with stronger purchasing power and better infrastructure; the southern corridor concentrates the top index values (see Figure 4).

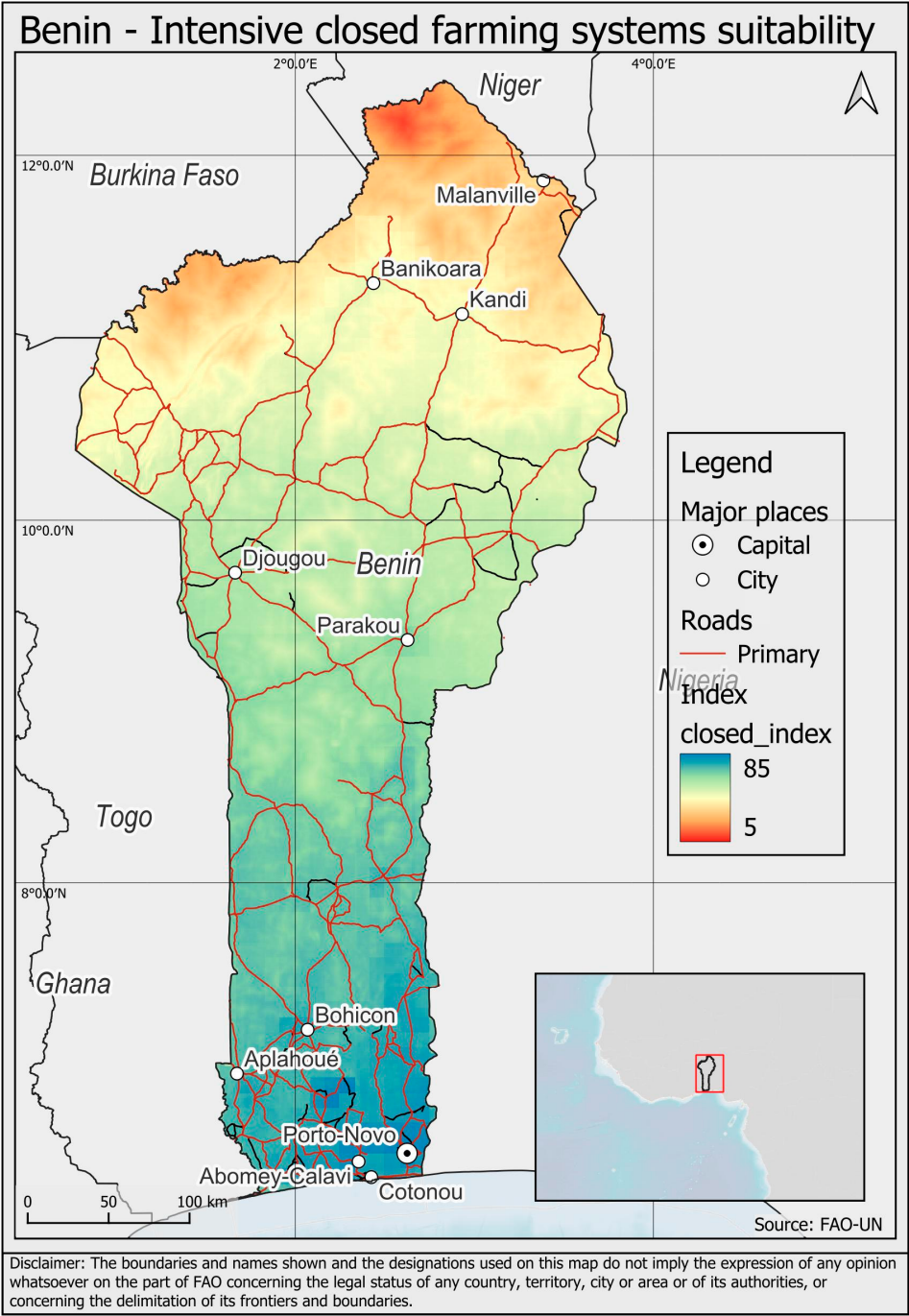


Figure 4. Intensive closed systems suitability index.

3.2.2. Recommended Locations

Applying exclusive criteria (road and banking proximity, ICT coverage) and constraints (flood-prone and dense urban areas) yields peri-urban belts as the best candidates. The Abomey-Calavi–Cotonou–Porto-Novo metropolitan region shows the most consistent concentration of suitable sites (see Figure 5). Site-level screening remains essential to avoid local conflicts and overly dense settings.

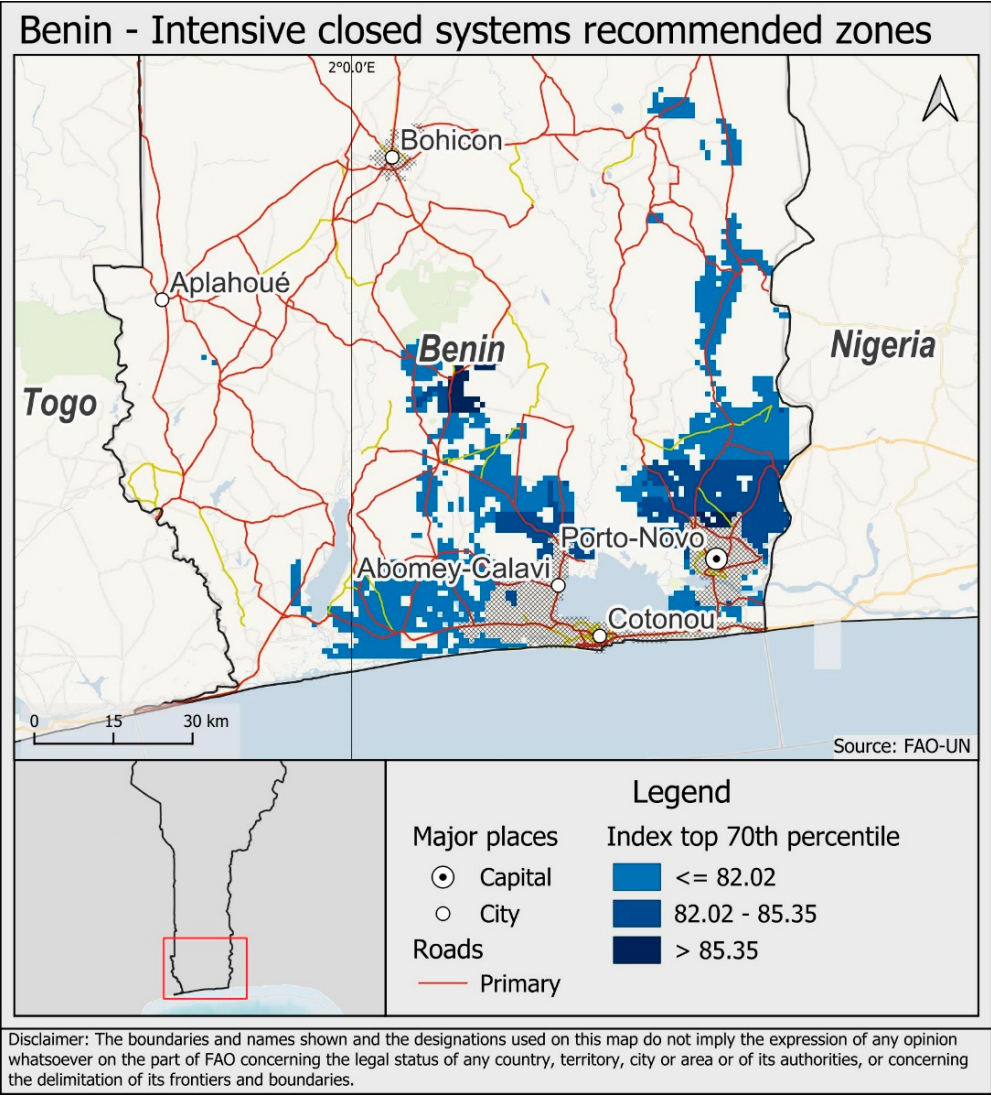


Figure 5. Intensive closed systems—final suitability map.

3.3. Open Intensive Tilapia Cage Systems

3.3.1. Suitability Index

Cage-system suitability is driven primarily by demand/access to markets, with highest values north of the Abomey-Calavi–Cotonou–Porto-Novo axis and along the corridor toward Aplahoué–Bohicon (see Figure 6). Central and northern provinces are generally limited by market access; Parakou is a notable exception.

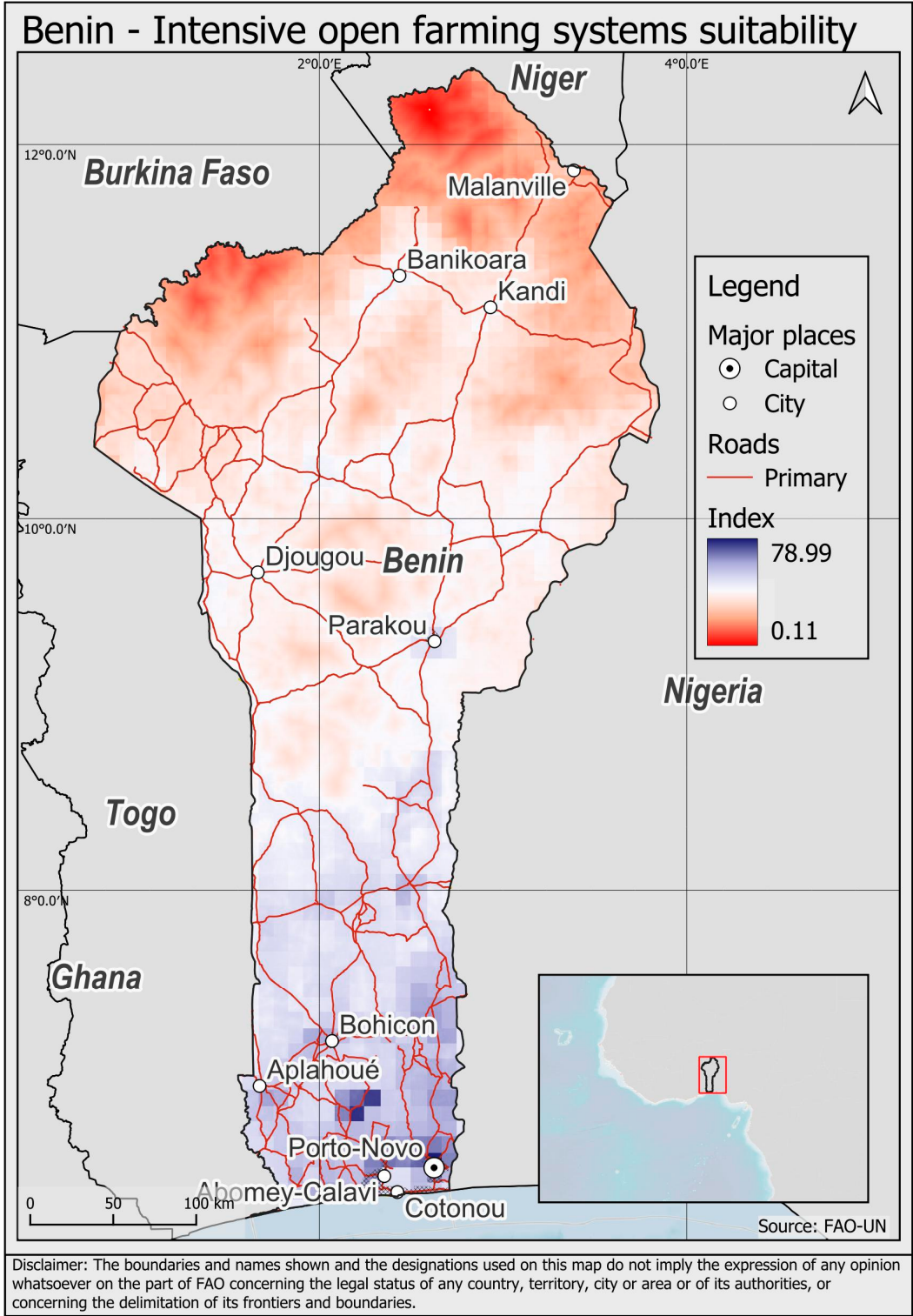


Figure 6. Open cage systems suitability index.

3.3.2. Recommended Locations and Constraints

Final mapping (2 km buffer of permanent water; top 70th percentile of suitability) identifies southern lakes—particularly Ahémé and Nokoué—as potential sites; Lake Nokoué requires brackish-water considerations. Additional opportunities include Zagnanado and Azili Lakes and the Ilauko Reservoir (see Figures 7–9). However, anthropogenic pressures (eutrophication, pollution, fecal contamination) reported for key waterbodies necessitate rigorous water-quality due diligence before deployment.

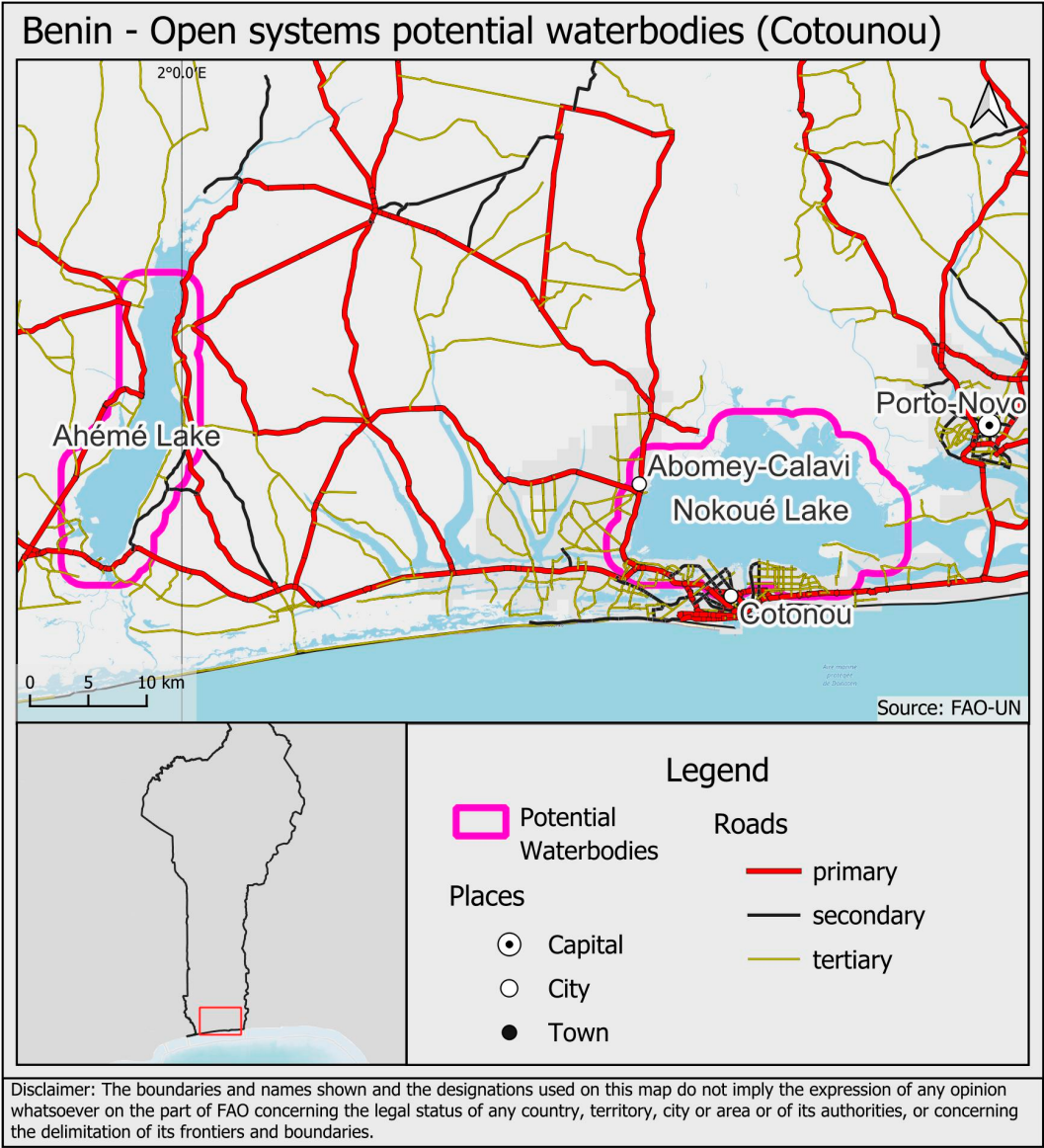


Figure 7. Potential sites for intensive tilapia cage farming systems (Cotonou).

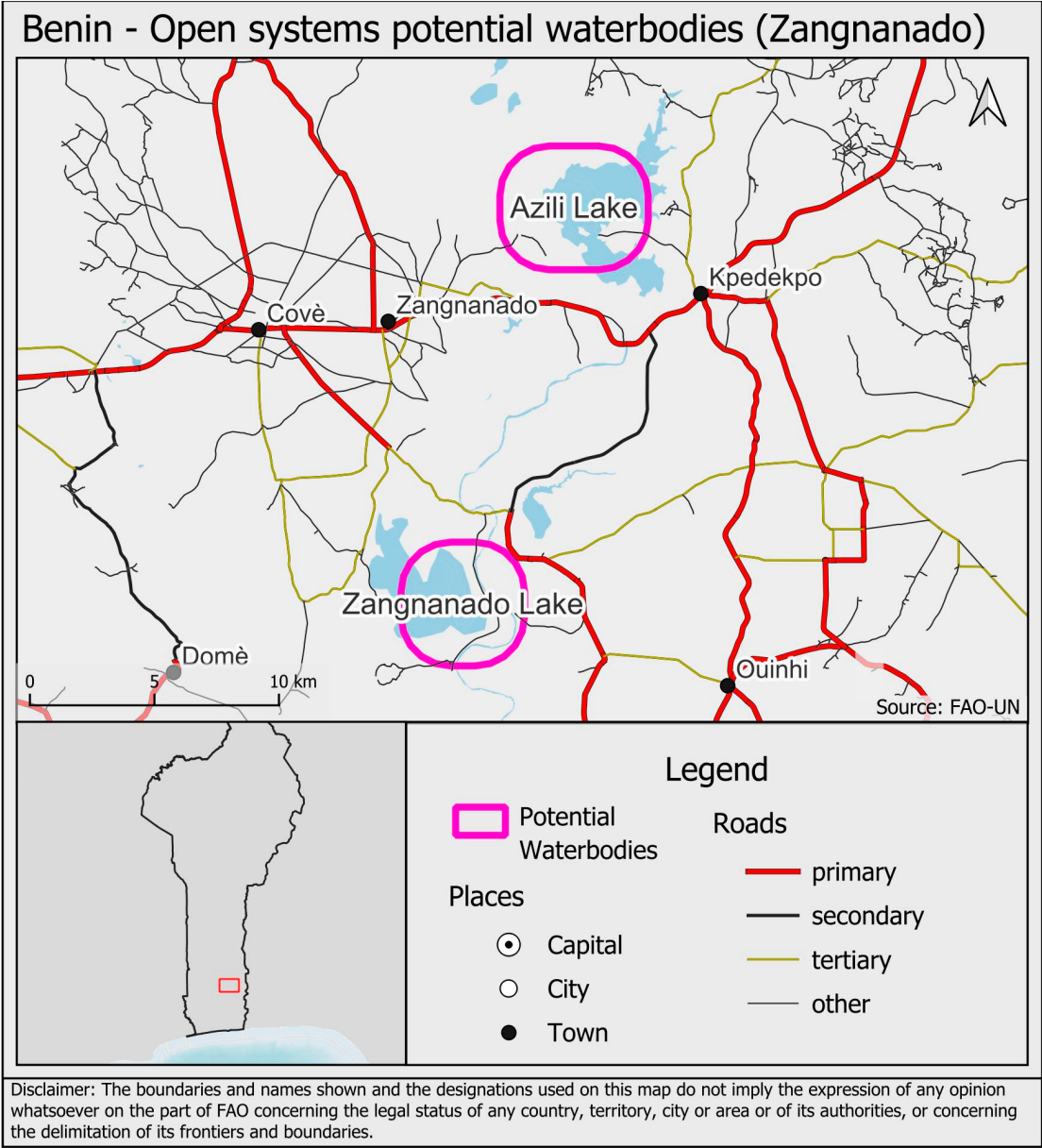


Figure 8. Potential sites for intensive tilapia cage farming systems (Zagnanado).

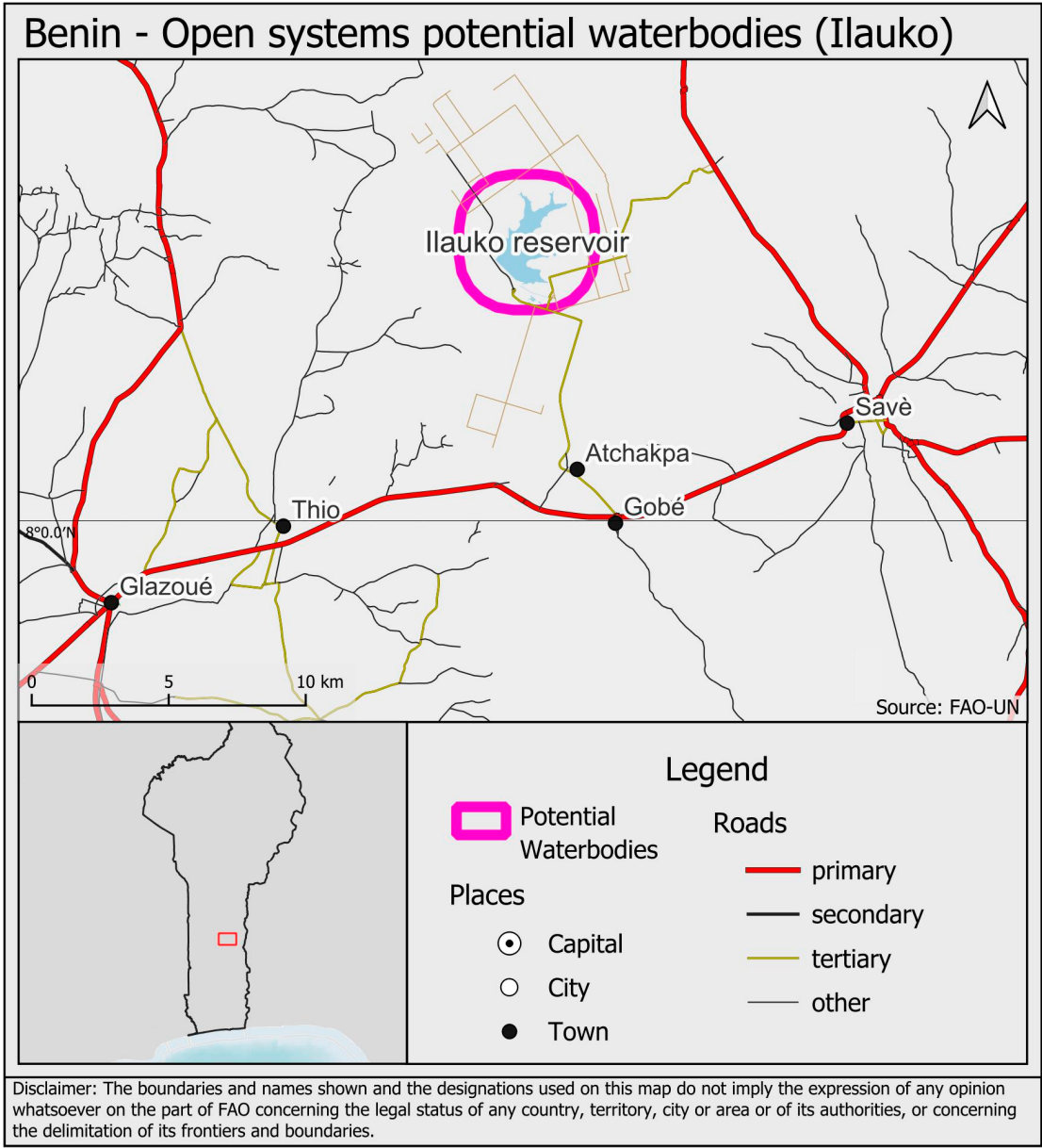


Figure 9. Potential sites for intensive tilapia cage farming systems (Ilauko).

3.4. Key Takeaways (All Systems)

- Demand proximity matters most for intensive systems; peri-urban southern corridors are consistently favored.
- Extensive/semi-intensive opportunities are widely distributed, with central–southern areas offering the strongest cluster of high suitability.
- Open cage systems show promise in major southern lakes, contingent on environmental safeguards and brackish-water accommodation where relevant.

4. Discussion

This study mapped suitability and priority areas for three fish farming systems types across the Republic of Benin and examined how the resulting patterns can be interpreted considering our working assumptions and prior evidence. For extensive/semi-intensive systems, the north–south gradient—with broader suitability in the south and central belt and lower suitability toward the extreme north/northwest—reflects the dependence of small-scale operations on natural and geographic factors (water balance, soils/slope) and locally accessible inputs from crops and livestock by-products. The priority index further indicates where high suitability coincides with lower wealth

indicators, suggesting where interventions may yield outsized benefits in terms of poverty reduction, food security, and nutrition.

For peri-urban intensive closed systems (ponds, tanks, flow-through and RAS), the dominance of market accessibility in the suitability index underscores the commercial nature of these systems: where infrastructure, services and purchasing power concentrate, so do viable peri-urban sites. At the same time, operational reliability hinges on energy access; the growing use of solar/PV to power pumps, aeration and recirculation partially mitigates grid limitations but requires up-front capital and technical capacity[26,27].

Open tilapia cage systems show highest potential around major southern lakes (e.g., Ahémé and Nokoué) and peri-urban corridors with strong demand. However, environmental exchanges inherent to open cages—waste discharge, pathogen transfer, fish escape—require proactive safeguards, especially in waterbodies already affected by eutrophication and pollution. Prior studies in Lake Nokoué and the Lower Ouémé Valley document organic and bacteriological contamination (e.g., total and thermotolerant coliforms, *E. coli*) linked to wastewater, runoff and household activities [28,29]. In Lake Nokoué, brackish conditions also necessitate appropriate strain/management choices and post-harvest handling adapted to the cold-chain constraints of tilapia distribution[30,31].

Methodologically, the results validate a pragmatic, multi-criteria approach using normalized grids and explicit constraints/eligibility masks. For permanent water masks, the Global Surface Water seasonality layer (seasonality = 12) is an appropriate source; demand-side accessibility can be complemented by mobile broadband coverage as a proxy for ICT access [32–34].

Policy and investment implications follow from these patterns. For extensive/semi-intensive systems, extension services and micro-finance should target the central–southern cluster and the high-priority communes identified by the index. For intensive closed systems, peri-urban belts around Abomey-Calavi–Cotonou–Porto-Novo merit enterprise development support that couples market access with reliable energy solutions (including PV) and business services. For open cages, any promotion around Ahémé, Nokoué, Zagnanado/Azili and Ilauko must be conditional on water-quality baselines, continuous monitoring, stakeholder consultation, and enforceable rules that minimize conflicts with other users and protect aquatic ecosystems[28,29].

Future research should (i) integrate seasonal hydrology and groundwater into the water balance; (ii) assess climate-sensitive risks (flood, temperature extremes) and their interaction with energy reliability for closed systems; (iii) compile high-resolution market and logistics layers (e.g., ice plants, cold rooms, feeder roads) to refine demand accessibility; (iv) evaluate brackish tilapia production options for Nokoué under different salinity regimes; and (v) perform participatory ground-truthing to calibrate thresholds and to quantify economic viability under realistic input/output price scenarios[26,30].

5. Conclusions

- Extensive/semi-intensive systems suitability is widely distributed but strongest across the central–southern belt; prioritizing communes where high suitability overlaps lower wealth can amplify impacts on poverty, food security and nutrition.
- Peri-urban intensive closed systems are primarily demand-driven: peri-urban belts around major southern urban centres concentrate suitable sites; enterprise development should link market access with reliable energy (including PV) and business/financial services[26,27].
- Open tilapia cage systems have focal opportunities in southern perennial waterbodies (e.g., Ahémé, Nokoué, Zagnanado/Azili, Ilauko), but deployment must be contingent on water-quality safeguards, brackish-water management where applicable, and clear governance to manage competing uses[28,29,35].
- Across systems, near-term priorities are site-specific ground-truthing, environmental due diligence, and producer-centred extension; medium-term priorities include building market/logistics data layers and integrating seasonal/climate risks into the suitability framework. [36]

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Abbreviations

The following abbreviations are used in this manuscript:

Abbreviation	Definition
AI	Artificial intelligence
AWI	Asset Wealth Index
COVID-19	Coronavirus disease 2019
CRS	Coordinate reference system
CSI	Digital FAO and Agro-Informatics Division (FAO)
DEM	Digital elevation model
ESA	Economic and Social Development Stream (FAO)
FAO	Food and Agriculture Organization of the United Nations
GDAL	Geospatial Data Abstraction Library
GDP	Gross domestic product
GIS	Geographic information system
GLW4	Gridded Livestock of the World, version 4
GRASS	Geographic Resources Analysis Support System
GSMA	GSM Association
GSW	Global Surface Water
ICT	Information and communication technology
IFPRI	International Food Policy Research Institute
JRC	Joint Research Centre (European Commission)

MAPSPAM	MapSPAM—Global Spatially-Disaggregated Crop Production Statistics
MCDA	Multi-criteria decision analysis
MCE	Multi-criteria evaluation
MDPI	Multidisciplinary Digital Publishing Institute
NFI	Fisheries and Aquaculture Division (FAO)
NSA	Animal Production and Health Division (FAO)
OSM	OpenStreetMap
PCP	Precipitation
POI	Point of interest
PV	Photovoltaic
QGIS	QGIS Geographic Information System
RAS	Recirculating aquaculture system
RET	Reference evapotranspiration
ROI	Return on investment
WaPOR	FAO Water Productivity through Open access of Remotely sensed derived data

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