

A MULTI-SCALAR FRAMEWORK FOR AGRICULTURAL DESALINATION IN THE CHTOUKA-AIT BAHA WEF-NEXUS

UN CADRE À L'ÉCHELLE MULTIPLE POUR LE DESSALEMENT À DES FINS AGRICOLES DANS LE LIEN ENTRE EAU-ALIMENTATION- ENVIRONNEMENT DE CHTOUKA-AIT BAHA

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ABSTRACT

In the Souss-Massa basin of southwestern Morocco—a critical horticultural center contributing 9% to the national agricultural GDP—systemic overexploitation has resulted in an annual groundwater deficit of 270 million m³. This study introduces a comprehensive multi-scalar framework to evaluate the structural transition from historical phreatic water to sustainable, non-conventional agricultural desalination. By integrating the Macro-scale (Water-Energy-Food-Ecosystems [WEF] Nexus and regional hyper-drought trends), the Meso-scale (Infrastructural network reliability and Public-Private Partnership [PPP] economic assessment), and the Micro-scale (Qualitative nutrient precision, soil physics, and circular brine valorization). It is a framework that reanalyses water security by proving that agricultural survival in arid regions requires moving beyond localized field interventions toward a cohesive, multi-scalar paradigm. By decoupling vital food systems from climate volatility, this model alters the agricultural desalination narrative from municipal "absolute purity" to an optimized, "fit-for-purpose" qualitative model. Furthermore, the integration of a circular bioeconomy reclaims the environmental liability of reverse osmosis brine, converting a hazardous waste stream into a productive engine for aquaculture and halophytic biomass production. As groundwater reserves reach global bankruptcy, this multi-scalar blueprint bridges the critical gaps between macro policy, infrastructure reliability, and micro-level soil chemistry. It stands as an essential, scalable global benchmark for engineering long-term climate resilience and securing national water sovereignty.

Keywords: Agricultural desalination; annual groundwater deficit; water security; biomass production.

RESUME

Dans le bassin du Souss-Massa, situé au sud-ouest du Maroc — un centre horticole essentiel contribuant à l'ordre de 9% au PIB agricole national — la surexploitation systémique a donné lieu à un déficit annuel des eaux souterraines de 270 millions de m³. Cette étude présente un cadre global à l'échelle multiple visant à évaluer la transition structurelle de l'utilisation historique des eaux phréatiques au recours à un dessalement agricole durable et non conventionnel. Il intègre l'échelle macro (lien entre eau-énergie-alimentation-écosystèmes [WEF] et tendances régionales en matière d'hyper-sécheresse), l'échelle méso (fiabilité du réseau d'infrastructures et évaluation économique des partenariats public-privé [PPP]) et l'échelle micro (précision qualitative des nutriments, physique des sols et valorisation circulaire des eaux salées). Il s'agit d'un cadre qui analyse de nouveau la sécurité hydrique en démontrant que la survie de l'agriculture dans les régions arides nécessite d'aller au-delà des

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interventions localisées sur le terrain vers un paradigme cohérent à l'échelle multiple. En dissociant les systèmes alimentaires vitaux de la volatilité climatique, ce modèle réoriente le discours sur le dessalement agricole, passant d'une «pureté absolue» municipale à un modèle qualitatif optimisé et «adapté à l'usage». De plus, l'intégration d'une bioéconomie circulaire reprend la contrainte environnementale liée à l'eau salée issue de l'osmose inverse, en transformant un flux de déchets dangereux en une force productive pour l'aquaculture et la production de biomasse halophyte. Alors que les réserves d'eaux souterraines arrivent à un état de faillite à l'échelle mondiale, ce plan d'action à l'échelle multiple comble les lacunes critiques entre la politique macroéconomique, la fiabilité des infrastructures et la chimie des sols au niveau micro. Il constitue une référence mondiale essentielle et évolutive pour garantir la résistance au climat à long terme et assurer la souveraineté nationale en matière d'eau.

Mots-clés : Dessalement agricole; Déficit annuel des eaux souterraines; Sécurité hydrique; Production de biomasse.

1. Introduction: The Global and National Imperative for Desalination:

1.1 The Global Water Distribution Paradox:

Water covers about 71% of the Earth's surface, representing a total volume of roughly 1.386 billion km³. However, this apparent abundance hides a severe resource limitation: freshwater accessible for direct human, industrial, and agricultural use accounts for only 3.5% of this total volume, while the oceans and seas sequester 96.5% as saltwater. Within the global freshwater pool, 68.7% is locked in glaciers and polar ice sheets, 30.1% is stored in deep underground aquifers, and a mere 0.3% exists as accessible surface water in lakes, rivers, and wetlands.(Figure 1A)

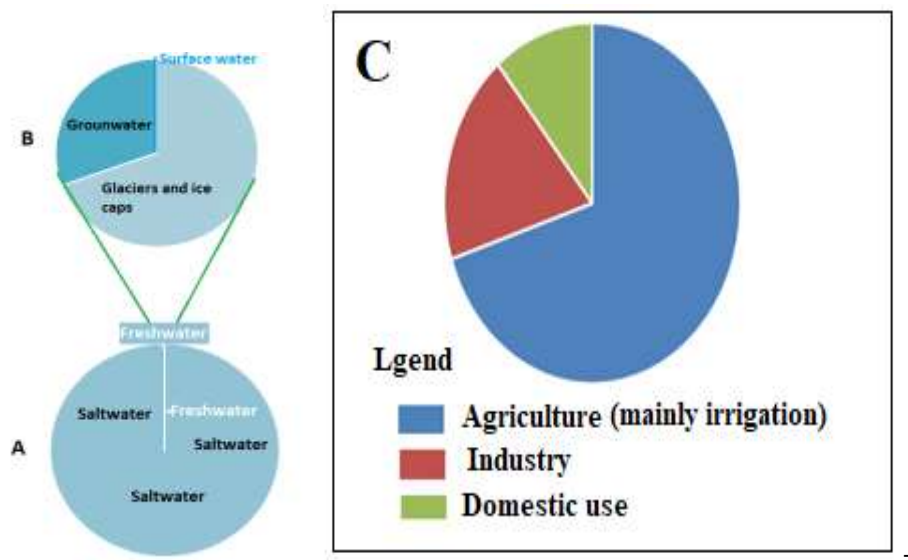


Figure1. Distribution of Water on Earth Data Source: USGS – Water Science School, 2023. A- Fresh and Salt Water distribution and B- Fresh Water distribution C- Global Distribution of Freshwater Use by Sector (Data Source: FAO – AQUASTAT, 2022)

On a global scale, the Food and Agriculture Organization (FAO) reports that agriculture is the dominant consumer of freshwater resources, accounting for roughly 70% of total withdrawals. (Figure 1 C). In arid and semi-arid nations, this agricultural allocation surges to 85–90%. In Morocco, the irrigated sector consumes approximately 85% of the country's available water resources, highlighting the profound pressure placed on natural water resources by intensive food production system.

1.2 Morocco's Structural Plunge into Severe Water Scarcity:

Over the past six decades, Morocco has transitioned from a position of relative water security to a state of chronic, structural scarcity. Demographic growth, climate-induced shifts in meteoric precipitation, and aggressive agricultural expansion have driven five times decline in per capita water availability. (Table 1)

Table1. Evolution of Per Capita Water Allocation in Morocco (Source: Word Bank (2022 Report); Ministry of Infrastructure and Water).

Year	Per Capita Water Allocation (m ³ /capita/year)	Hydrological Vulnerability Classification
1960	2,500	Comfortable situation
1990	1,200	Water stress
2000	950	Water scarcity
2010	731	Water scarcity
2020	632	Severe water scarcity
2024	500	Absolute Scarcity / Survival Threshold
2030 (projection)	450	Extreme Anthropogenic Scarcity

This structural trend is intensified by a sequence of increasingly severe, multi-decadal drought waves that have systematically dismantled Morocco's surface water reserves. (Table 2)

Table2. Main Drought Waves in Morocco

Historical Period	Climatological & Hydrological Characteristics	Pivot in National Water Policy
1940 – 1945	Prolonged, multi-year meteorological drought that devastated traditional, rainfed cereal systems and local livestock	Traditional Relief: Initiated localized, state-subsidized grain distribution and primitive well drilling.
1980 – 1985	High-intensity drought cycle that caused widespread failure of surface storage and triggered a major economic contraction.	The Great Dam Policy: Accelerated the construction of large-scale dam infrastructure to maximize surface water retention.
2018 – 2023	Six consecutive years of unprecedented rainfall deficit; the lowest inflows in the nation's recorded hydrological history.	The Non-Conventional Pivot: Enforced emergency urban water boundary and accelerated the Seawater Desalination Program.

According to projections by the World Resources Institute (WRI), Morocco will face extremely highwater stress by 2040, with up to 80% of its conventional water resources potentially compromised by climate change and depletion. This reality has forced a strategic pivot toward non-conventional water resources; positioning seawater desalination as a critical pillar for regional economic survival and national food sovereignty.

2. Geographical, Geological, and Socio-Economic Profile of the Chtouka-Ait Baha Region

2.1 Geographic Location and Administrative Framework:

The study area is located within the Chtouka-Ait Baha Province in the Souss-Massa region of southwestern Morocco (Figure 2), roughly 30 kilometers south of Agadir and directly east of the Souss-Massa National Park. The province spans a total surface area of 3,523 km², with a demographic footprint

of approximately 370,000 inhabitants distributed across two urban municipalities (Ait Baha and Biougra) and 20 rural municipalities.

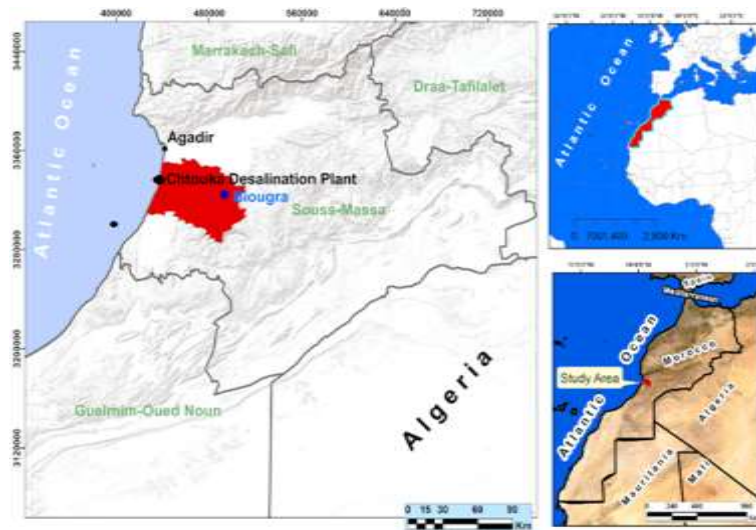


Figure 2. Location of the study area (Morocco: North-West Africa)

2.2 Climatological Matrix and High-Tech Agricultural Intensification:

The Chtouka plain features a highly arid, semi-arid template modulated by maritime winds from the Atlantic Ocean and the protective barrier of the Anti-Atlas mountain range. The mean annual rainfall is an ultra-low 165 mm/year, marked by profound spatial and inter-annual variability. The region experiences a highly compressed wet season from November to March, which accounts for 75% of total annual precipitation, followed by an absolute dry season from April to October.

Temperatures range from a winter mean of 12.5°C in January to an August mean exceeding 24.4°C. During summer Chergui events, hot Saharan air masses can push maximum daily temperatures to 49°C, driving extreme atmospheric vapor pressure deficits and severe evapotranspiration demands. Conversely, nocturnal relative humidity remains high (averaging 68–80%).

This climate has fostered a sophisticated agro-industrial sector. The province contains 84,950 hectares of Utilized Agricultural Area (UAA), of which 26,880 hectares are under intensive localized irrigation. Chtouka Ait Baha is the primary source of Morocco's high-value protected agriculture, utilizing advanced multi-span greenhouse complexes to produce over 50% of the nation's early vegetable exports, notably round tomatoes and green beans. This sector supplies 11% of total European Union annual tomatoes imports, climbing to 15% between November and March. The high-tech horticultural engine generates an annual added value of 9 billion MAD (8% of the national agricultural GDP) and sustains 35,000 specialized jobs, heavily supporting the regional economy.

2.3 Hydrogeological Framework and Hydraulic Bankruptcy:

The intensive agricultural model of Chtouka was built on a finite hydrogeological resource: the Chtouka Aquifer. This unconfined reservoir is hosted within Plio-Quaternary, Miocene, and Eocene formations composed of dune sandstones, calcarenites, and highly permeable fluvio-lacustrine deposits ranging from 50 to 200 meters in thickness. Over the past four decades, the expansion of private greenhouse perimeters reliant on uncontrolled tubewell drilling has generated a catastrophic imbalance in the aquifer's water budget. Historical water balance records from the Souss-Massa Hydraulic Basin Agency (ABHSM) document a severe trajectory of decline from 1996 to 2020:

- **1996:** Total Inflows (68 Mm³) vs. Total Outflows (56 Mm³) yielded a temporary surplus of +12 Mm³/year.
- **2003:** Total Outflows surged to 93 Mm³ against 35 Mm³ of climate-depleted inflows, inducing a deficit of -60 Mm³/year.
- **2020:** Net abstractions for irrigation reached 90 Mm³, pushing the total aquifer deficit to a record -63.2 Mm³/year.

This deficit caused a severe drop in the water table. Piezometric monitoring between 1968 and 2015 shows that 30% of the aquifer's core agricultural zone—specifically around the high-density pumping centers of Ait Amira and Biougra—suffered a water table drawdown exceeding 50 meters. An additional 30% experienced a drop of 30 to 50 meters, meaning that 80% of the entire aquifer footprint entered systemic depletion. (Figure 3)

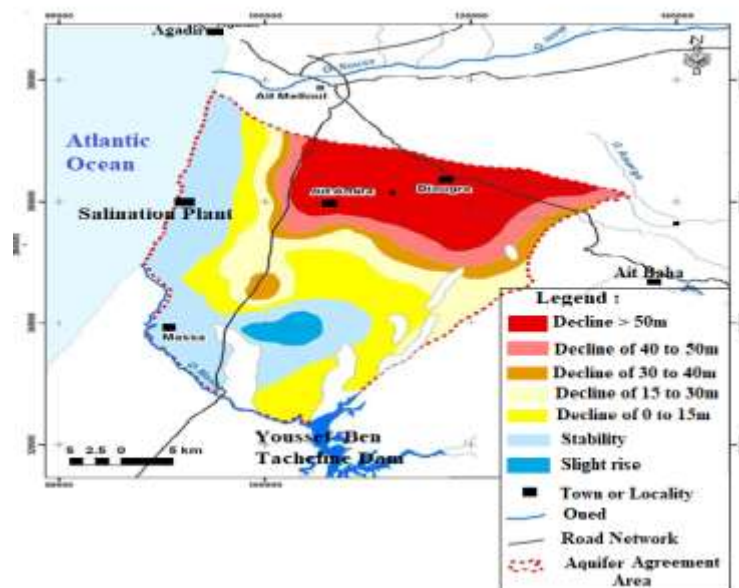


Figure3. Evolution of the Piezometric Surface between 1968 and 2015 (modified from: Aglagal Chaima & El Fitah Mariem, 2020)

This depletion caused the hydraulic gradient to flip along the coast. Atlantic Ocean saltwater began migrating inland to fill the depleted aquifer volume, with marine intrusion volumes surging from 3 Mm³ in 2012 to 10 Mm³ by 2020, salinizing 536 hectares of coastal land. This groundwater salinization forced farmers to drill deeper wells, driving pumping depths past 150 meters. The resulting rise in energy costs made water extraction financially unfeasible for many operators, leading to land abandonment and posing a major threat of rural exodus.

3. The Macro-Scalar Framework: The WEF-Nexus and Regional Sovereignty

To resolve this crisis, water planners must look beyond traditional, localized field interventions and adopt a Multi-Scalar Framework. The highest tier of this model, the Macro-Scale, integrates large-scale industrial engineering with regional policy, focusing on the Water-Energy-Food-Ecosystems (WEF) Nexus:

3.1 Decoupling Production from Climate Volatility

In arid zones, traditional water management relies heavily on meteoric inputs stored in surface dams. However, the Souss-Massa basin's severe drought cycles show that surface reservoirs can run dry during extended dry periods. The macro-scale framework addresses this vulnerability by decoupling regional food production from rainfall variability, replacing overexploited groundwater with a reliable, climate-independent seawater desalination grid.

3.2 The Energy-Water Loop and Net-Zero Operational Integration

Seawater Reverse Osmosis (SWRO) is highly energy-intensive. Operating an industrial facility on standard grid electricity can strain national energy systems and increase carbon emissions, shifting an environmental crisis from water to atmosphere. Morocco, which imports roughly 90% of its energy as fossil fuels, addresses this challenge through the "National Energy Efficiency Strategy"(SNEE), targeting a 52% renewable share in the electricity mix by 2030.

The Chtouka-Ait Baha project applies this strategy by coupling its 275,000 m³/day SWRO plant with a dedicated 150 MW wind farm. This clean energy system offsets the 68 MW of installed electrical load required by the plant's high-pressure pumps and energy recovery devices. By using wind power as a "hydraulic battery," the system balances energy and water needs, stabilizes water tariffs against volatile global fuel prices, and achieves operational carbon neutrality.

3.3 Institutional Cohesion and Source Diversification

The macro-scale framework aligns separate sectoral strategies—agricultural growth via the Green Morocco Plan / Generation Green 2020-2030 and water security via the PNAEPI 2020-2027(National Program for Drinking Water Supply and Irrigation)(Figure5), into a unified development plan. It balances food production goals with the need to protect local ecosystems. By substituting groundwater with desalinated water and treated wastewater across the Souss-Massa basin, the framework relieves pressure on regional aquifers, allowing natural groundwater levels to recover and safeguarding the nearby Souss-Massa National Park.



Figure5.The five pivots of the PNAEPI 2020-2027(National Program for Drinking Water Supply and Irrigation PNAEPI 2020-2027) (Modified from : Tahiri Khalid, 2023)

The PNAEPI 2020–2027 framework (Figure5), outlines a comprehensive, five-basis water strategy. It balances infrastructural expansion—via dam development and desalination—with conservation through multi-sectoral demand management and waste-water reutilisation. Moreover, the plan mentions social equity by reinforcing rural potable water supplies, all supported by communication and awareness initiatives to ensure long-term sustainability.

4. The Meso-Scalar Framework: Infrastructural Reliability and Economic Assessment

The Meso-Scale bridges macro-level regional policy with micro-level farm operations, focusing on the engineering of distribution networks, financial sustainability, and institutional risk management:

4.1 Industrial Engineering of the Chtouka Desalination Complex

The physical engine of the project is the Douira Seawater Desalination Plant (Figure 6), built within the coastal perimeter of the Souss-Massa National Park. The infrastructure incorporates a sub-sea open intake system designed to deliver raw seawater with an average Total Dissolved Solids (TDS) concentration of 40.9 g/L and an electrical conductivity (EC) of 54.3 mS/cm at a baseline temperature of 18°C.



Figure 6. Morocco desalination plant reverse osmosis industrial infrastructure Right: Overview Left: Equipments

To optimize performance and protect the reverse osmosis membranes from fouling during coastal algal blooms (where Suspended Solids reach 20 mg/L and the Silt Density Index averages 5), the plant uses advanced pre-treatment systems, including dissolved air flotation and ultrafiltration.

The plant operates at an initial production capacity of 275,000 m³/day, divided between two major consumer sectors: Potable Water Supply and the Agricultural Irrigation. An ongoing expansion project is designed to scale total capacity to 400,000 m³/day, evenly split at 200,000 m³/day for each sector.

4.2 High-Pressure Transmission and Local Distribution Networks

To deliver desalinated water from the coastal plant to inland farms, the project incorporates an extensive hydraulic distribution network:

- **Transmission:** Fresh water flows from the plant's 43,000 m³ buffer basin through a 23 km main high-pressure supply pipeline;
- **Storage:** The main pipeline feeds into a 12,000 m³ regulation basin located within the irrigation perimeter;
- **Distribution:** Five automated booster pumping stations regulate pressure across 487 km of primary and secondary distribution pipelines, connecting to 300 km of individual farm links;
- **Delivery:** The network supplies water to approximately 1,500 farms through 1,300 automated irrigation hydrants. Each hydrant delivers an optimized flow rate of 0.35 L/s/ha at a steady downstream pressure of 1 bar, providing a reliable and uniform water supply across the plain.

4.3 The Public-Private Partnership (PPP) Financial Vehicle

Building large-scale coastal infrastructure requires substantial capital expenditure (CapEx), which can strain public budgets. The Chtouka project addresses this by using a Public-Private Partnership (PPP) framework with a Design-Build-Operate-Transfer (DBOT) model, representing a total investment of 4.48 billion Dirhams.

The institutional framework combines two separate concession agreements through a single Pooling Contract (Contrat de Mutualisation) to balance costs by:

- **The Drinking Water Concession:** Structured between ONEE (National Office of Electricity and Drinking Water) and the private concessionaire SEDA (Agadir Desalination Company), managing urban drinking water delivery;
- **The Irrigation Concession:** Managed between MAPMDREF (Ministry of Agriculture, Maritime Fisheries, Rural Development, Water and Forests), the Regional Office for Agricultural Development- Souss Massa (ORMVA-SM), and the private company Aman El Baraka, regulating agricultural water delivery.

This contract shares the operational costs of seawater intake and primary filtration between municipal consumers and agricultural producers. This cost-allocation mechanism allows the project to offer a sustainable water tariff of approximately 5 DH/m³ to local farmers, making non-conventional water accessible for high-value agricultural production.

5 The Micro-Scalar Framework: Qualitative Nutrient Precision and Soil Physics:

The Micro-Scale focuses on water chemistry and its interaction with soil physics and plant physiology, modifying the emphasis from water volume to specific water quality by:

5.1 Remineralization

Seawater reverse osmosis membranes excel at removing salts, generating a permeate with very low Total Dissolved Solids (<250 mg/L) and minimal buffering capacity. However, this highly pure water can be corrosive and aggressive, posing a risk of damage to concrete and metallic distribution pipelines.

When applied directly to agriculture, unbuffered pure water can cause severe agronomic imbalances. It can disrupt the soil profile, strip essential nutrients from the soil matrix, and cause osmotic shock in plant root zones. To prevent these issues, agricultural desalination systems must incorporate post-treatment remineralization to ensure the water is chemically balanced and agronomically suitable.

The Chtouka facility utilizes automated post-treatment remineralization systems, injecting carbon dioxide (CO₂) and dissolving crushed calcite beds to enrich the water with essential minerals. Through the processes of pH adjustment, divalent cation enrichment, and SAR optimization, the water's chemical composition is altered to satisfy exact agricultural specifications.

5.2 Regulation of the Sodium Adsorption Ratio (SAR) and the Soil Dispersal Mechanics

The interaction between irrigation water and soil health is governed by the Sodium Adsorption Ratio (SAR), which measures the relative concentration of monovalent sodium ions against divalent calcium and magnesium ions. If irrigation water exhibits an elevated SAR or low electrical conductivity (EC), sodium ions can dominate the soil's cation exchange complexes. This dominance causes clay particles to swell and disperse, fracturing soil aggregates, sealing macro-pores, and reducing soil permeability and aeration.

To prevent soil structural breakdown, the Chtouka project optimizes post-treatment remineralization to keep the irrigation water's SAR within safe limits relative to its conductivity, satisfying the stringent criteria outlined in irrigation water quality standards.

5.3 Secondary Boron treatment

While standard reverse osmosis membranes are highly effective at rejecting ionic salts, they have a lower rejection rate for uncharged, small neutral molecules like boric acid (H₃BO₃). At typical seawater pH levels (pH=8.0), boron exists primarily as uncharged boric acid, which can pass through standard membrane matrices and remain in the treated water. High-value horticultural crops are highly sensitive to boron concentrations. For ultra-sensitive crops like avocado, citrus, and certain berries, boron levels above 0.5–1.0 mg/L can cause phytotoxicity, leading to marginal leaf chlorosis, necrosis, stunted crop growth, and reduced yields.

To safeguard high-value export crops, agricultural desalination systems must incorporate secondary treatment stages. This is typically achieved by raising the pH of the primary reverse osmosis permeate to 9.5, which converts boric acid into the negatively charged borate anion (B(OH)₄⁻), allowing secondary low-pressure membranes to reject it effectively and keep boron concentrations safely below 0.5 mg/L.

6 The Circular Bioeconomy: Transforming Brine default into Ecological Resources:

A major challenge of agricultural desalination, particularly for inland treatment facilities, is the management of concentrated reverse osmosis brine. Field survey (En-nija Btissame & Tazi Fatima Zahra, 2025) across the Chtouka plain (Figure 7) show that current brine management practices are fragmented and present environmental risks, and shared this proportions:

- **9%** of farms utilize a advanced two-stage reverse osmosis system, which increases the water recovery rate from 70% to 92%, reducing the total volume of brine reject;
- **9%** discharge concentrated brine directly into unprotected earthen pits without geomembrane liners, causing salt infiltration that can raise the salinity of neighboring boreholes;

- **37%** reuse brine for dust suppression on farm pathways;
- **45%** blend brine effluents with freshwater to irrigate resilient green spaces or salt-tolerant cover crops.

Thus to improve sustainability, the multi-scalar framework introduces a zero-waste, circular bioeconomy model that treats brine as a resource for cascaded aquaculture and halophytic biomass production. We suggest:

6.1 Aquaculture: Brackish Nile Tilapia (*Oreochromis niloticus*)

The first step of the circular model channels agricultural brine discharges (salinity 0.6 to 2.01 g/L) into specialized aquaculture ponds to farm Nile Tilapia (*Oreochromis niloticus*), a hardy, euryhaline fish species that tolerates moderate salinity. And advantageous by its:- Operational Parameters: The aquaculture system maintains a pH between 6.5 and 8.5, dissolved oxygen levels ≥ 4 mg/L, and a stocking density of 4 to 5 fish/m³. The region's consistent warmth provides favorable conditions for tilapia growth;

Economic Profile: Tilapia production is highly efficient; local production costs average 8–12 MAD/kg, while wholesale market prices range from 20–30 MAD/kg, creating a profitable secondary income stream for operators.

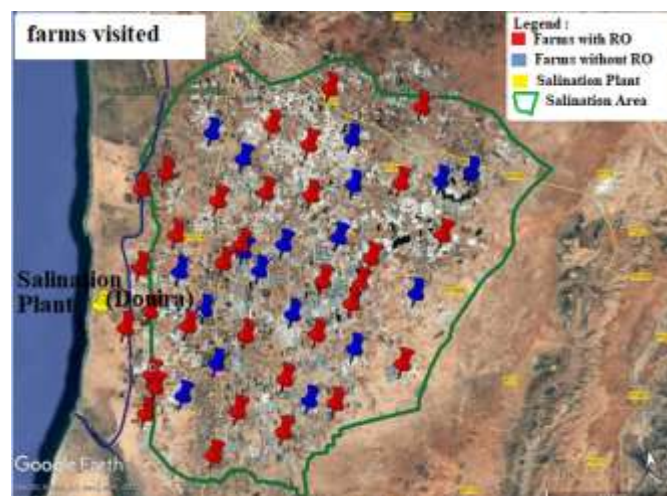


Figure 7. Carte de distribution des fermes visitées (Modified from : En-Naija Btissame & Tazi Fatima Zahra, 2025)

6.2 Cultivation of Adaptable Vegetation: *Atriplex* and *Quinoa*

This circular model uses nutrient-enriched aquaculture wastewater to irrigate high-yield, salt-tolerant crops like the following:

- **Atriplex (*Atriplex nummularia*):** Aligned with Morocco's Generation Green 2020–2030 strategy, this deep-rooted, drought-tolerant halophytic shrub serves as vital livestock forage. A single plant yields 2.5–3 kg of dry matter annually. Because large-scale cultivation requires contiguous blocks of roughly 100 hectares, smallholder space constraints are bypassed via a centralized management model led by cooperatives or public-private partnerships to efficiently collect and distribute aquaculture brine;
- **Quinoa (*Chenopodium quinoa*):** This annual halophytic grain thrives in alkaline soils (pH 8.08–8.6) and tolerates water salinity up to 15,000 $\mu\text{S}/\text{cm}$ through internal ion exclusion. Field trials show that deficit irrigation during the vegetative phase saves 19% of water without

impacting final grain yield. Quinoa produces 1.5–2.5 tonnes/hectare, securing lucrative returns at 10–20 MAD/kg.

6.3 *Solar Crystallization : Near-Zero Liquid Discharge (ZLD)*

The final stage channels the remaining high-salinity drainage from the halophytic plots into lined solar evaporation ponds. Solar energy concentrates the remaining liquids into solid crystal salts, which can be harvested for industrial or agricultural applications. This step prevents unmanaged brine discharge, protects local groundwater and soil from Stalinalisation, and achieves Near-Zero Liquid Discharge (ZLD) to complete the circular model.

7 Conclusion: A Multi-Scalar Blueprint for Climate Resilience

The Chtouka-Ait Baha framework redefines the frontier of arid-region water management by demonstrating that the transition from catastrophic groundwater depletion to long-term agricultural sustainability cannot be achieved through isolated, field-level interventions alone. Instead, it demands a synchronized, multi-scalar approach that seamlessly bridges macro-level policy, meso-level infrastructural reliability, and micro-level agronomic precision. By successfully decoupling a vital 1.5 billion DH export engine from climate and rainfall volatility, this project proves that seawater desalination—when powered by dedicated renewable energy—can serve as a crucial pillar for regional socio-economic stability and national food sovereignty.

Beyond merely securing alternative water volumes, this framework drives a critical paradigm shift in agricultural engineering. It moves away from standard municipal "absolute purity" treatment models toward highly automated, "fit-for-purpose" remineralization strategies that meticulously safeguard soil physics, regulate the Sodium Adsorption Ratio (SAR), and prevent crop boron toxicity.

Finally, the integration of a zero-waste circular bioeconomy transforms the traditional environmental bottleneck of desalination—concentrated reverse osmosis brine—into a valuable ecological asset. By establishing a cascading loop that flows from brackish aquaculture to halophytic forage and grain production, and ultimately to solar crystallization, the model achieves a Near-Zero Liquid Discharge (ZLD) status. As aquifers face systemic bankruptcy worldwide, the Chtouka-Ait Baha nexus stands as a premier global benchmark, demonstrating how engineering innovation can harmonize intensive food production with profound ecosystem restoration in the face of hyper-drought.

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