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Potentials for Sustainable Irrigation in Humid Climate Zones: Building a Case for Sierra Leone's Climate and Ecologies

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Abstract Irrigation is conventionally framed as an arid-land technology, yet the fastest relative growth in irrigated area now occurs in humid and sub-humid regions, where rainfall is abundant in total but poorly distributed within the year. This review examined the physical, agronomic, and institutional potentials for sustainable irrigation in humid climate zones and applied the resulting framework to Sierra Leone, a country receiving 1,900–4,000 mm of rainfall annually yet growing a single rain-fed crop on most of its farmland. Published hydrological assessments, global irrigation-expansion modelling, humid-region field trials, and national land and water statistics were synthesised. Sierra Leone holds internal renewable water resources of about 160 km³ yr⁻¹ against agricultural withdrawals of roughly 0.33 km³ yr⁻¹, under 0.3% of the resource, while only about 1,000 ha of a technically assessed 807,000 ha potential had been equipped. The binding constraint was therefore temporal and infrastructural rather than volumetric: the December–March dry season delivers only 6–7% of annual rainfall against open-water evaporation of 1,200–1,900 mm yr⁻¹, producing a seasonal deficit that idles 1.165 million ha of lowlands, of which inland valley swamps account for about 690,000 ha. Global modelling indicated that soft-path irrigation using small monthly storage, combined with 20% deficit irrigation, could sustainably expand irrigation over about 8 million ha in sub-Saharan Africa without depleting environmental flows, a far better match to Sierra Leone's runoff regime than large annual storage. Humid temperate evidence showed supplemental irrigation raised yields with modest application, with water-use efficiency declining as depletion thresholds were relaxed. Against this, climate simulations consistently showed irrigation suppresses dry-heat extremes but raises wet-bulb temperature, potentially intensifying moist-heat stress where tolerance margins are already narrow. Sierra Leone should therefore prioritise small-scale, gravity-fed development in inland valley swamps with water-balance scheduling and externality monitoring.

Keywords: *sustainable irrigation, humid climate zones, inland valley swamps, dry-season cropping, soft-path water storage, supplemental irrigation*

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1. Introduction

Irrigation is conventionally treated as a response to aridity. Roughly 70% of global freshwater withdrawals serve agriculture, and the canonical irrigated landscapes , the Indus and Nile basins, the North China Plain, the Central Valley of California, the Spanish Mediterranean, are places where rainfall alone cannot sustain a crop [1,2]. This framing has shaped both engineering practice and development policy, so that humid tropical countries with rainfall exceeding 2,000 mm yr⁻¹ have frequently been classified as having no irrigation problem at all.

That classification confuses annual totals with seasonal availability. In monsoonal and other strongly seasonal humid climates, the wet season delivers water in excess of crop demand, often in excess of soil infiltration and drainage capacity, while the dry season delivers almost none. The agronomic consequence is a single cropping cycle per year on land that is physically capable of supporting two or three. Even within the wet season, dry spells of two to three weeks can coincide with flowering or grain filling, producing yield losses that no amount of seasonal surplus can retroactively repair [3]. Recent analyses of irrigation adoption in humid regions have confirmed this logic empirically: the fastest relative growth in irrigated area in the United States has occurred not in the arid West but in humid eastern and midwestern states, where irrigation functions primarily as insurance against episodic drought and as a means of stabilising yields on sandy soils with low

water-holding capacity [4,5].

Sierra Leone presents this paradox in an extreme form. Annual rainfall ranges from about 1,900 mm in the north-east to more than 4,000 mm along the coastal Freetown peninsula, with a national mean commonly reported between 2,526 and 2,690 mm [6,7]. Internal renewable water resources are approximately 160 $km^3\ yr^{-1}$, and total agricultural withdrawal is on the order of 0.33 $km^3\ yr^{-1}$, so less than 1% of the renewable resource is used [7,8]. Yet rice, the national staple, consumed at among the highest per-capita rates in West Africa, is grown predominantly under rain-fed conditions on a single annual cycle, and national production has persistently fallen short of consumption, requiring substantial imports [9,10]. Against a technically assessed irrigation potential of about 807,000 ha, the area equipped for irrigation has been estimated at roughly 1,000 ha [7,11].

The gap between resource endowment and resource use invites a specific question, which this review addresses: what forms of irrigation are technically appropriate, hydrologically sustainable, and economically defensible in humid climate zones, and what does the answer imply for Sierra Leone's particular configuration of climate, land, and institutions? Three considerations make the question non-trivial. First, humid-zone irrigation economics differ fundamentally from arid-zone economics because the marginal product of applied water is smaller and more variable; systems must be justified against risk reduction and cropping intensification rather than against the difference between zero and full yield [4,12]. Second, humid soils and shallow water tables mean that excess water is a recurrent agronomic hazard, so irrigation design cannot be separated from drainage design [13,14]. Third, and least widely appreciated, irrigation modifies the surface energy balance in ways that reduce dry-heat extremes but increase near-surface humidity and wet-bulb temperature, an effect that recent coordinated modelling has quantified and that carries particular significance for tropical humid regions already close to thermal tolerance limits [15,16,17,18].

The objectives of this review were therefore to (i) characterise the hydro-climatic signature of humid climate zones that creates irrigation demand despite rainfall surplus; (ii) assemble and harmonise the available evidence on Sierra Leone's water resources, land ecologies, and current irrigation status; (iii) synthesise the international evidence base on sustainable irrigation expansion, soft-path storage, and supplemental irrigation performance in humid settings; (iv) evaluate the environmental and climatic trade-offs of humid-zone irrigation, including the moist-heat externality; and (v) derive a staged, ecology-specific development pathway for Sierra Leone together with the research and monitoring needed to support it.

2. Methods and Materials

2.1. Review Design

This study was conducted as a structured, evidence-based review with a regional case application. It combined (i) a synthesis of peer-reviewed literature on irrigation in humid and sub-humid climates, (ii) extraction of quantitative hydro-climatic and land-resource data for Sierra Leone from national and international assessments, and (iii) a comparative appraisal of irrigation-expansion scenarios derived from global hydrological modelling. No new field experimentation was undertaken; the contribution lay in assembling dispersed evidence into a coherent framework for a country and a climate class that the irrigation literature has largely bypassed.

2.2. Literature Identification and Inclusion

Peer-reviewed articles, agency assessments, and technical extension publications appearing between 1979 and 2026 were examined, with emphasis on material published after 2015. Sources were retained when they satisfied at least one of four criteria: (i) they quantified irrigation water requirements, water availability, or sustainable irrigation potential at national, regional, or global scale with humid regions distinguishable in the results; (ii) they reported field or farm-scale performance of irrigation in a climate receiving more than 700 mm of annual rainfall; (iii) they characterised Sierra Leone's rainfall, evaporation, water resources, land ecologies, or irrigation infrastructure; or (iv) they quantified the biophysical or climatic side-effects of irrigation, including energy-balance, humidity, and heat-extreme responses. Studies reporting only arid-zone results without a humid comparator were used solely for methodological context.

2.3. Data Harmonisation

Quantities extracted from heterogeneous sources were converted to a common set of units before comparison: mm for depths of rainfall, evaporation, evapotranspiration, and irrigation application; $km^3\ yr^{-1}$ for water resource volumes and withdrawals; hectares for land areas; $kg\ ha^{-1}$ for yields; and $kg\ m^{-3}$ for water-use efficiency. Where sources reported ranges arising from different observation periods or gauge networks, the range was preserved rather than averaged, because the spread itself is informative about the reliability of humid-tropical hydrological data. Where a single figure was reported by multiple agencies with differing base years, the most recent traceable value was adopted and the alternative noted.

2.4. Analytical Framework

The assessment of irrigation potential followed a three-tier logic that separates questions frequently conflated in policy discussion.

Tier 1: volumetric sufficiency. Whether the renewable water resource is adequate in aggregate, expressed as the ratio of total withdrawal to internal renewable water resources. This tier establishes whether water scarcity in the classical sense constrains expansion.

Tier 2: temporal availability. Whether water is present when crops require it. This tier was evaluated by comparing dry-season rainfall with reference evapotranspiration and open-water evaporation, and by considering the storage volume implied by the resulting deficit. The distinction between soft-path storage (small structures buffering water within a month) and hard-path

storage (large reservoirs buffering water across seasons) was applied here, following the scenario definitions used in global sustainable-irrigation modelling [19].

Tier 3: deliverability and sustainability. Whether abstraction, conveyance, and application can be achieved at acceptable capital cost, without violating environmental flow requirements, degrading water quality, or generating unacceptable secondary effects. Environmental flow protection was treated as a binding constraint rather than a residual, consistent with the sustainability criteria adopted in the modelling literature [19,20].

Sierra Leone's ecologies were then assessed individually against the three tiers, because the country's lowland classes differ so markedly in hydrology, salinity risk, and engineering requirement that a single national irrigation prescription would be inappropriate.

2.5. Treatment of Climate Feedback Evidence

Evidence on irrigation–climate feedbacks was drawn from coordinated multi-model experiments and from single-model sensitivity studies. Because these experiments prescribe idealised irrigation, typically the full satisfaction of soil-moisture deficits over all present-day or potential irrigated areas, their magnitudes were interpreted as indicative of the sign and relative strength of effects rather than as forecasts of the consequences of Sierra Leone's own irrigation development. Agreement across independent models was treated as the principal criterion for confidence.

2.6. Limitations of the Evidence Base

Three limitations shaped the analysis. Sierra Leone's hydrometric network was substantially degraded during the 1991–2002 civil conflict, so long continuous discharge records are scarce and several widely cited water-resource figures derive from modelled or pre-conflict estimates. Second, no multi-season, replicated irrigation trials in Sierra Leone's inland valley swamps were located in the peer-reviewed literature, requiring the use of analogues from other humid regions. Third, published irrigation-potential figures for the country rest on land-suitability assessments whose assumptions about acceptable capital cost are not always stated, so they should be read as upper bounds on physically irrigable area rather than as economically justified targets.

3. Results and Synthesis

3.1. The Hydro-Climatic Signature of Humid Irrigation Demand

Humid climate zones generate irrigation demand through three mechanisms that operate independently of annual water balance.

The first is seasonal concentration. In tropical humid West Africa, a single rainy season delivers the overwhelming majority of annual precipitation, and the dry season is effectively rainless. Table 1 summarises Sierra Leone's rainfall regime. The four driest months, December through March, contribute approximately 6–7% of annual rainfall, while reference evapotranspiration continues at 3–5 mm d^{-1} and open-water evaporation over the year reaches 1,200–1,900 mm. A dry-season crop therefore faces a water requirement of roughly 400–600 mm against rainfall of perhaps 100–180 mm, a deficit that must be supplied from storage, from shallow groundwater, or from residual stream flow.

The second is intra-seasonal variability. Even in the wet season, dry spells of 10–20 days are common, and their coincidence with sensitive phenological stages produces disproportionate yield loss. Supplemental irrigation addressing such spells requires small volumes but high reliability, and the economic case rests on avoided loss rather than on incremental production [4,12].

The third is soil-related. Humid tropical soils are frequently coarse-textured and highly weathered, with low water-holding capacity and rapid drainage, so that a nominal rainfall surplus does not translate into plant-available water storage. The same characteristic explains why irrigation adoption in the humid United States has concentrated on sandy soils where the available water reservoir may sustain a crop for only a few days [4,5]. Ferralsols and Acrisols, which dominate Sierra Leone's uplands, typically hold 60–120 mm of plant-available water in the effective root zone, equivalent to 12–25 days of unstressed transpiration at dry-season rates [24,25].

Table 1. Rainfall and evaporation characteristics relevant to irrigation demand in Sierra Leone

Characteristic	Reported value or range	Implication for irrigation
Annual rainfall, national range	1,900–4,000 mm	Aggregate surplus; no volumetric scarcity
Annual rainfall, national mean	2,526–2,690 mm	Among the highest in West Africa
Rainy season	May–October (peak July–September)	Excess water; drainage the primary constraint
Dry season	December–March	6–7% of annual rainfall; full irrigation requirement
Open-water evaporation	1,200–1,900 mm yr^{-1}	Storage losses material; shallow ponds inefficient
Reference evapotranspiration, dry season	approx. 3–5 mm d^{-1}	Dry-season crop demand approx. 400–600 mm
Internal renewable water resources	approx. 160 km^3 yr^{-1}	Abundant relative to any plausible demand
Agricultural water withdrawal	approx. 0.33 km^3 yr^{-1}	Under 0.3% of renewable resource

3.2. Sierra Leone's Land Ecologies and Their Irrigation Suitability

Sierra Leone's agricultural land divides into uplands of about 4.2 million ha and lowlands of about 1.165 million ha, the latter comprising four hydrologically distinct classes (Table 2). This division is the pivot of the national irrigation question, because the lowland classes offer very

different combinations of water availability, engineering requirement, and environmental risk.

Inland valley swamps, at roughly 690,000 ha the largest lowland class, are narrow valley bottoms that receive lateral seepage and concentrated runoff from surrounding uplands. Water tables remain shallow into the early dry season, and simple bunding, peripheral drains, and small headwater weirs can extend water control for a second crop with minimal pumping. They are consequently the lowest-cost entry point for irrigation development, and the class in which most existing partially water-controlled area is found [26,27].

Bolilands, about 145,000 ha of saucer-shaped depressions in the north and centre, flood deeply in the wet season and dry out abruptly. They demand drainage before they demand irrigation, and their potential lies in extending the cropping window at both ends of the wet season rather than in true dry-season production [28].

Riverine grasslands, about 130,000 ha along the major rivers, offer reliable dry-season abstraction but require pumping, flood protection, and careful sequencing with river regime, making them capital-intensive but capable of supporting higher-value cropping [29].

Mangrove swamps, about 200,000 ha of tidal estuarine land, are agriculturally productive under controlled conditions but carry acute salinity and acid-sulphate risks, and their ecological value as fish nursery and coastal protection argues for conservative development [30,31].

Table 2 Agro-ecological land classes in Sierra Leone and their assessed irrigation characteristics

Ecology	Area (ha)	Dry-season water source	Principal engineering requirement	Relative cost
Uplands	4,200,000	Rainfall only	Rainwater harvesting, small reservoirs	High per hectare
Inland valley swamps	690,000	Seepage, shallow water table, headwater storage	Bunding, peripheral drains, small weirs	Low
Bolilands	145,000	Residual soil water, shallow wells	Drainage first, then supplemental supply	Moderate
Riverine grasslands	130,000	Perennial river abstraction	Low-lift pumping, flood protection	Moderate to high
Mangrove swamps	200,000	Tidal fresh-water lens, controlled sluicing	Salinity control, tidal gates, acidity management	High, constrained
Total lowlands	1,165,000	—	—	—

3.3. The Scale of the Development Gap

The contrast between assessed potential and realised development is stark. Against an irrigation potential of about 807,000 ha, the area equipped for irrigation has been reported at approximately 1,000 ha, or roughly 0.1% of potential. Even allowing generously for partially water-controlled swamp area not captured in formal statistics, the equipped share remains a fraction of one percent. For comparison, agricultural withdrawal of 0.33 km³ yr⁻¹ against internal renewable resources of 160 km³ yr⁻¹ implies that irrigating the full 807,000 ha at a generous net requirement of 600 mm would consume on the order of 4.8 km³ yr⁻¹, approximately 3% of the renewable resource. Volumetric availability is not the constraint; storage, conveyance, energy, and institutional capacity are [32].

3.4. Soft-Path versus Hard-Path Irrigation Expansion

Global modelling of sustainable irrigation expansion under baseline and 3°C-warmer conditions provides the most directly relevant scenario evidence for humid regions [19]. That analysis distinguished soft-path approaches, in which runoff is buffered in small storage over monthly timescales, from hard-path approaches requiring large annual reservoirs, and imposed environmental flow requirements as a constraint on abstraction in both cases. Its principal findings, summarised in Table 3, carry three implications for Sierra Leone.

First, soft-path expansion alone was found to support about 140 million ha of additional sustainable irrigation globally under baseline climate, falling to about 53 million ha under a 3°C-warmer climate, a demonstration that the soft path is climate-sensitive but far from negligible. Second, adding 20% deficit irrigation to soft-path storage recovered a substantial additional area, indicating that modest under-application is a more efficient route to expansion than additional storage capacity. Third, in sub-Saharan Africa specifically, soft-path expansion combined with deficit irrigation was estimated to permit sustainable irrigation over about 8 million additional hectares, close to an 80% increase relative to present sustainably irrigated area in the region. Complementary work has shown that sustainably intensifying rain-fed and irrigated systems together could benefit populations on the order of hundreds of millions, with the soft path supporting roughly 70 million ha of expansion and the hard path a substantially larger area at correspondingly greater cost [19,20,21].

Table 3. Sustainable irrigation expansion potential under alternative storage pathways

Scenario	Global additional sustainably irrigated area	Behaviour under 3°C warming	Relevance to Sierra Leone
Soft path, full irrigation (small monthly storage)	approx. 140 million ha	Falls to approx. 53 million ha	Directly applicable; matches valley-bottom hydrology
Soft path plus 20% deficit irrigation	Substantial increment above soft path	Retains more area than full irrigation	Preferred; lowers storage and pumping demand
Hard path (large annual storage)	Largest total area	Least sensitive to warming	Poor fit; high cost, evaporation and displacement
Sub-Saharan Africa, soft path plus deficit	approx. 8 million ha (approx. 80% increase)	—	Regional benchmark for national ambition

The soft-path framing matches Sierra Leone's hydrology closely. Runoff is generated in large quantities over a five- to six-month wet season, and the buffering required to irrigate a dry-season crop in an inland valley swamp is measured in weeks rather than in years. Small headwater storage, valley-bottom water retention, and shallow groundwater abstraction all fall within the soft-path category and avoid both the displacement burden and the evaporative penalty of large reservoirs, the latter non-trivial where open-water evaporation reaches 1,200–1,900 mm yr^{-1}.

3.5. Field Evidence from Humid Regions

Evidence from humid production systems, summarised in Table 4, converges on a consistent picture: irrigation in humid climates pays through risk reduction and cropping intensification, and conservative application outperforms generous application on a per-unit-water basis.

A three-year, four-site on-farm demonstration in humid southern Michigan compared maximum allowable depletion (MAD) thresholds of 60% (under-irrigated), 50% (recommended), and 30% (over-irrigated) in maize and soybean, applying approximately 19, 25, and 32 mm per event respectively [22]. Irrigated yields exceeded non-irrigated yields in both crops, but maize yield was nearly identical across the three depletion thresholds, with no statistically significant differences detected, while water-use efficiency declined monotonically as irrigation volume increased. Soybean behaved similarly, with only the non-irrigated treatment separating from the rest. The practical inference is that in humid settings the yield response curve flattens at low application depths, so the economically and hydrologically efficient strategy is the most conservative one that still averts stress, precisely the logic of deficit irrigation embedded in the soft-path scenarios.

In humid temperate Poland, a study of Braniewo county mapped crop water shortages against available shallow groundwater in a region receiving about 641 mm of annual precipitation [23]. Water needs of the principal crops reached 430–550 mm, and water shortages of 40–120 mm occurred in most years, rising to 120–160 mm on heavier soils in roughly one year in five. Shallow groundwater was generally adequate in volume but frequently required treatment for iron, manganese, or ammonia before use in pressurised systems, a caution directly relevant to Sierra Leone, where shallow well water in lateritic terrain is commonly iron-rich.

In the humid United States, irrigated area in humid states has more than tripled over recent decades, and about 57% of national irrigated acreage is now sprinkler-served with higher shares in humid regions [4]. Analysis of centre-pivot adoption in Illinois framed these systems explicitly as drought-risk mitigation: their returns concentrate in drought years, they interact with federal crop insurance coverage, and they enable crop switching and cropland expansion in addition to yield protection. Extension guidance for humid regions correspondingly emphasises water-balance or "checkbook" scheduling, in which rainfall is credited and evapotranspiration debited daily so that irrigation is applied only when the root-zone balance approaches a management threshold [13].

Table 4. Selected field and regional evidence on irrigation performance in humid climates

Location and climate	System and treatments	Principal finding	Inference for humid-zone practice
Southern Michigan, USA; humid continental	Overhead sprinkler; MAD 60/50/30% (19/25/32 mm per event), maize and soybean, 2021–2023, four sites	Irrigated exceeded non-irrigated yields; no significant yield difference among MAD thresholds; water-use efficiency declined with volume	Conservative scheduling maximises return per unit water
Braniewo county, Poland; humid temperate, 641 mm yr^{-1}	Groundwater-based supplemental irrigation assessment	Crop water needs 430–550 mm; shortages 40–120 mm typical, 120–160 mm in one year in five; groundwater often iron- and manganese-rich	Groundwater is viable but water quality must be tested
Illinois and eastern USA; humid continental	Centre-pivot irrigation systems	Adoption driven by drought-year returns, insurance interaction, crop switching and cropland expansion; humid-state irrigated area more than tripled	Value proposition is risk mitigation, not routine supply
Humid eastern USA, extension practice	Water-balance (checkbook) scheduling	Daily crediting of rainfall against evapotranspiration prevents both under- and over-application	Scheduling method of choice where rainfall is frequent

Climate Feedbacks of Irrigation in Humid Settings

Four independent modelling studies were examined for evidence on how irrigation modifies temperature and humidity extremes, and their agreement is notable.

The coordinated Irrigation Model Intercomparison Project experiment, using six Earth system models, found that irrigation made dry-heat extremes at least four times less likely over irrigated regions, but that the cooling benefit weakened substantially, and in places reversed, when heat stress was measured in moist-heat terms that account for humidity [15]. A single-model analysis with GISS ModelE reached the same conclusion at finer granularity: irrigation produced little or no change in median wet-bulb temperature in some regions but significant increases of 0.1–0.6°C in others, with quantiles between roughly the 50th and 90th percentiles warming significantly, and the number of months per year exceeding a 27°C wet-bulb threshold increasing at many hot locations [16]. Analysis of heat-wave classes showed dry heat waves declining and humid heat waves increasing, with effects detectable beyond irrigated areas through atmospheric transport [17]. More recent work reported that wet-bulb temperature rose while dry-bulb temperature fell under irrigation, that the moist-heat penalty was larger under a high-emission pathway, and that representing dynamic vegetation altered the magnitude of the response [18].

The implication for humid tropical West Africa is direct

rather than academic. Sierra Leone's wet-season wet-bulb temperatures already approach values at which sustained outdoor labour becomes hazardous, and dry-season irrigation would raise near-surface humidity during the one part of the year when atmospheric moisture is comparatively low. The effect of small-scale, dispersed irrigation on a few tens of thousands of hectares would be locally confined and far smaller than the idealised basin-scale irrigation prescribed in these experiments, but the sign of the effect is consistent across models, and it argues for monitoring wet-bulb conditions in scheme command areas as irrigation expands, and for scheduling field operations accordingly.

4. Discussion

4.1. Reframing Irrigation for Humid Climates

The evidence assembled here supports a reframing of what irrigation is for in a humid country. In arid systems, irrigation is the enabling condition of agriculture: without it, yield approaches zero. In humid systems, irrigation performs three narrower but valuable functions. It extends the cropping calendar, converting one rain-fed crop into two or, in favourable valley bottoms, into a crop-plus-vegetable sequence. It buffers intra-seasonal dry spells, protecting yield already largely paid for in seed, fertiliser, and labour. And it de-risks investment, making it rational for a farmer or a lender to commit to improved varieties and purchased inputs that would otherwise be gambled on rainfall.

Each of these functions has a distinct engineering implication. Calendar extension requires seasonal water availability and therefore storage or groundwater, but tolerates modest reliability. Dry-spell buffering requires little water but high reliability and rapid deployment. De-risking requires that the system be affordable enough that its cost does not itself become the dominant risk. Systems designed for arid-zone full replacement satisfy none of these efficiently, which helps explain the poor performance record of large imported irrigation schemes in humid West Africa.

4.2. Why Sierra Leone's Endowment Favours the Soft Path

Three features of Sierra Leone's physical geography align with soft-path development. The country's dense drainage network means that few potential command areas are far from a stream, reducing conveyance distance and lift — the same factor identified as favouring irrigation economics in the humid United States, where proximity to abundant streams lowers capital requirements [4]. Its inland valley swamps concentrate water naturally, so that the hydraulic work of collecting runoff is performed by topography rather than by engineering. And its rainfall reliability, while variable in timing, is high in total, so that small storage refilled repeatedly through the wet season can deliver a large seasonal yield of water from a small structure — exactly the mechanism that gives soft-path scenarios their leverage in global modelling [19].

Set against this, high open-water evaporation of 1,200–1,900 mm yr^{-1} penalises shallow, large-surface storage; deep, compact structures or subsurface storage in valley-bottom soils are hydrologically preferable. Two further considerations reinforce the soft path. Sierra Leone's electricity grid does not reach most agricultural areas, so pumped schemes imply diesel or solar generation, both of which raise unit water cost and maintenance burden; gravity and low-lift options avoid this. Solar-powered pumping has reduced the energy penalty considerably in comparable settings, but capital cost, theft risk, and maintenance depth remain material, so lifecycle costing is essential [33,34]. And scheme governance capacity is the historical binding constraint in West African irrigation, with small, farmer-managed systems consistently outperforming large agency-managed schemes in operation and maintenance [35,36].

4.3. Deficit Irrigation as the Default, Not the Exception

The Michigan demonstration and the soft-path-plus-deficit scenarios point in the same direction from very different methodological starting points [19,22]. Because the humid-zone yield response to applied water flattens quickly, the crop is not starting from zero, the last increments of applied water buy little yield while consuming storage, energy, and pumping capacity. Applying about 80% of full requirement therefore extends a given water supply across substantially more area at minor yield cost, and in the Michigan trials the yield cost was not even statistically detectable across a two-fold range of application depth. For Sierra Leone, where the objective is to bring the largest possible area under some water control rather than to maximise yield on a small area, deficit irrigation should be the design assumption from the outset rather than a drought contingency [37,38].

4.4. Drainage and Water Quality as Co-Requirements

In humid zones, excess water damages crops at least as often as deficit does. Waterlogging in bolilands and in valley bottoms during peak rainfall suppresses root respiration, promotes disease, and delays field operations; the Michigan work explicitly noted that excess soil moisture constrains yield and that over-irrigation carried disease implications [22]. Any irrigation intervention in Sierra Leone's lowlands must therefore be conceived as water control, the capacity to add and to remove water, rather than as water supply. Peripheral and interceptor drains in inland valley swamps serve both functions, admitting seepage in the dry season and evacuating surplus in the wet [39,40].

Water quality is the second co-requirement. The Polish assessment found that shallow groundwater, though volumetrically sufficient, frequently exceeded acceptable iron, manganese, and ammonia concentrations for irrigation use [23]. Sierra Leone's lateritic and acid-sulphate soils make elevated iron and, in mangrove terrain, low pH and high sulphate likely. Where drip or micro-sprinkler equipment is contemplated, filtration and periodic acid or chlorine maintenance must be budgeted,

since emitter clogging by iron precipitates is a common cause of premature system failure. In mangrove ecologies, salinity intrusion during the late dry season constrains the feasible cropping window and requires tidal gate management informed by measured conductivity rather than by calendar [41,42].

4.5. The Moist-Heat Trade-Off

The consistent modelling finding that irrigation reduces dry-heat extremes while increasing wet-bulb temperature deserves explicit treatment in humid-tropical planning, not because it invalidates irrigation but because it changes what should be monitored [15,16,17,18]. In arid regions, the humidity increase is offset by a large temperature reduction, and irrigation is unambiguously protective of human thermal comfort. In humid regions, the temperature reduction is smaller and the humidity increase lands on an atmosphere already near saturation, so the net effect on physiological heat stress may be adverse.

The practical response is proportionate rather than precautionary in the restrictive sense. Sierra Leone's plausible irrigation development, tens of thousands of hectares over a decade, dispersed across many small valley-bottom schemes, is orders of magnitude below the idealised, contiguous irrigation prescribed in the intercomparison experiments, and the resulting regional atmospheric signal would be small. Nonetheless, local effects within and immediately downwind of command areas are real, and the appropriate measures are cheap: record wet-bulb globe temperature at scheme level [48,49], schedule labour-intensive operations to early morning, and prefer irrigation methods that wet a smaller fraction of the surface, furrow, drip, or alternate-furrow application, over full-surface flooding where crop and soil permit [50]. This also aligns with water-saving objectives, making it a rare case in which the mitigation of a climatic externality coincides with the primary efficiency goal.

4.6. Institutional and Economic Considerations

The technical case does not translate automatically into adoption. Three institutional conditions emerge from the comparative evidence. First, risk instruments matter: centre-pivot adoption in the humid United States interacted strongly with crop insurance, whose coverage of maize and soybean rose from 87% and 85% in 2016 to 96% and 93% in 2020 [4]. Sierra Leone has no comparable instrument, so the full drought risk sits with the farmer, and irrigation must compete against risk-avoidance strategies such as planting less land or fewer purchased inputs. Second, market access determines whether a second crop is worth growing; dry-season vegetable production is only attractive where produce can reach an urban market before spoiling, which ties irrigation returns to feeder roads and to cold chain in a way that arid-zone staple irrigation does not [43,44]. Third, land tenure in lowlands is frequently negotiated seasonally, and investment in bunds, drains, and weirs requires security of use across several years to be recoverable [45].

Costing deserves candour. At an indicative net dry-season requirement of 400–600 mm and typical application efficiencies of 50–70% for surface systems and 75–90% for pressurised systems, gross water requirements fall between roughly 450 and 1,200 mm per season. Gravity-fed swamp development can be achieved at low cost per hectare largely through labour, whereas pumped riverine schemes involve equipment, fuel, and maintenance costs that require a high-value crop to service. Staging development from the cheapest ecology upward is therefore not merely a technical preference but an economic necessity given fiscal constraints [46,47].

4.7. A Staged Development Pathway

Synthesising the foregoing, a three-phase pathway follows from the evidence. The first phase concentrates on inland valley swamps, using bunding, peripheral drainage, and small headwater retention to secure a reliable second crop with gravity or minimal lift, coupled with checkbook scheduling training and shallow-well water quality screening. The second phase addresses bolilands through drainage-led water control that extends the cropping window at both ends of the wet season, and introduces small solar-pumped supplemental systems for high-value crops where markets exist. The third phase, contingent on demonstrated management capacity, develops riverine grasslands with low-lift pumping and flood protection for commercial horticulture, while mangrove ecologies are approached conservatively with salinity monitoring and explicit protection of nursery and coastal-defence functions.

Each phase should carry a measurement obligation: crop water productivity in kg m^{-3}, water table and abstraction records, water quality, and wet-bulb conditions. Without such records, the country will continue to plan irrigation from land-suitability maps and imported design assumptions rather than from its own performance data.

4.8. Limitations

This review synthesised published evidence and did not generate new field measurements, so its quantitative claims about Sierra Leone rest on secondary sources of uneven vintage and provenance. National water resource and irrigation potential figures derive in part from pre-conflict surveys and modelled estimates, and the widely cited 807,000 ha potential reflects physical suitability rather than economic viability. No replicated multi-season irrigation trials from Sierra Leone's own inland valley swamps were available, so the agronomic inferences drawn from Michigan and Poland are analogical and require local verification, particularly regarding depletion thresholds appropriate to lowland rice and to vegetable crops on hydromorphic soils. Finally, the climate feedback evidence comes from idealised large-scale irrigation experiments whose magnitudes cannot be scaled down mechanically to the dispersed, small-area development envisaged here; only the direction of the effect should be treated as established.

5. Conclusions and Recommendations

5.1. Conclusions

This review of sustainable irrigation potential in humid climate zones, applied to Sierra Leone, supported the following conclusions. First, humid-zone irrigation demand arises from the temporal distribution of rainfall, from intra-seasonal dry spells, and from low soil water-holding capacity, not from any deficiency in annual totals; Sierra Leone receives 1,900–4,000 mm yr^{-1} yet obtains only 6–7% of it during the December–March period when irrigation would be required. Second, water availability does not constrain expansion: internal renewable water resources of about 160 km^3 yr^{-1} are drawn upon by agriculture at about 0.33 km^3 yr^{-1}, and irrigating the entire assessed potential of 807,000 ha would consume on the order of 3% of the renewable resource. Third, the development gap is extreme, with roughly 1,000 ha equipped against 807,000 ha of assessed potential and 1.165 million ha of lowlands, of which inland valley swamps constitute about 690,000 ha. Fourth, global scenario modelling showed that soft-path storage combined with 20% deficit irrigation could sustainably expand irrigation over about 8 million ha in sub-Saharan Africa, an approach matched to Sierra Leone's runoff regime and far preferable to hard-path annual reservoirs given open-water evaporation of 1,200–1,900 mm yr^{-1}. Fifth, humid-region field evidence showed no statistically significant yield differences among maximum allowable depletion thresholds of 30%, 50%, and 60% while water-use efficiency declined with application volume, establishing conservative deficit scheduling as the efficient default. Sixth, groundwater is a viable dry-season source in humid settings but frequently requires quality treatment, with iron and manganese the recurrent constraints. Seventh, irrigation in humid climates functions economically as drought-risk mitigation and cropping intensification rather than as a routine production input, which links its viability to insurance, market access, and tenure security. Eighth, multiple independent Earth system model studies agreed that irrigation reduces dry-heat extremes by a factor of four or more while raising wet-bulb temperature, so humid-zone irrigation carries a moist-heat externality that should be monitored and partially mitigated through irrigation-method choice and work scheduling.

5.2. Recommendations

Development should proceed from the cheapest and most forgiving ecology upward, beginning with inland valley swamps under gravity or low-lift supply, and treating bolilands as a drainage problem before an irrigation one. Deficit irrigation at approximately 80% of full requirement should be adopted as the design basis rather than as a contingency, and scheduling should follow a locally parameterised water-balance method that credits rainfall daily rather than a fixed calendar. Irrigation and drainage should be designed as a single water-control system in every lowland intervention. Shallow groundwater should be screened for iron, manganese, and salinity before pressurised systems are specified, and filtration and maintenance provisions should be costed from the outset. A national programme of replicated, multi-season trials in inland valley swamps is needed to establish depletion thresholds, crop water productivity, and drainage criteria for local soils and cultivars, since the present evidence base for the country's own conditions is essentially empty. Hydrometric and meteorological network rehabilitation should accompany scheme development so that future planning rests on measured rather than modelled hydrology. Finally, scheme-level monitoring of wet-bulb conditions, water table behaviour, water quality, and in coastal ecologies, salinity and mangrove extent should be built into programme design, so that the environmental and human-health trade-offs of humid-zone irrigation are managed with evidence rather than assumed away.

Data Availability Statement

No primary data, models, or code were generated during this study. All data, models, and information analysed appear in the submitted article or are available in the published sources cited in the References.

Practical Applications

Sierra Leone receives some of the highest rainfall in West Africa, yet almost all of its farmland grows only a single rain-fed crop each year because the December to March dry season is nearly rainless. This review shows that the country's irrigation problem is not a shortage of water overall, but the timing of that water and the lack of storage and infrastructure to hold it for dry-season use. Drawing on international evidence, it argues that small, low-cost, gravity-fed schemes in inland valley swamps, combined with modest deficit irrigation and day-by-day water-balance scheduling, offer the most affordable and sustainable path to a second annual crop. It also flags a practical caution: irrigation can raise humid-heat stress, so schemes should monitor working conditions and water quality. For planners and extension services, the message is to start with the cheapest ecologies, design irrigation and drainage together, and build measurement into every scheme.

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