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Water Stress in the Ewaso Ngiro North Basin: Insights from Integrated Modeling

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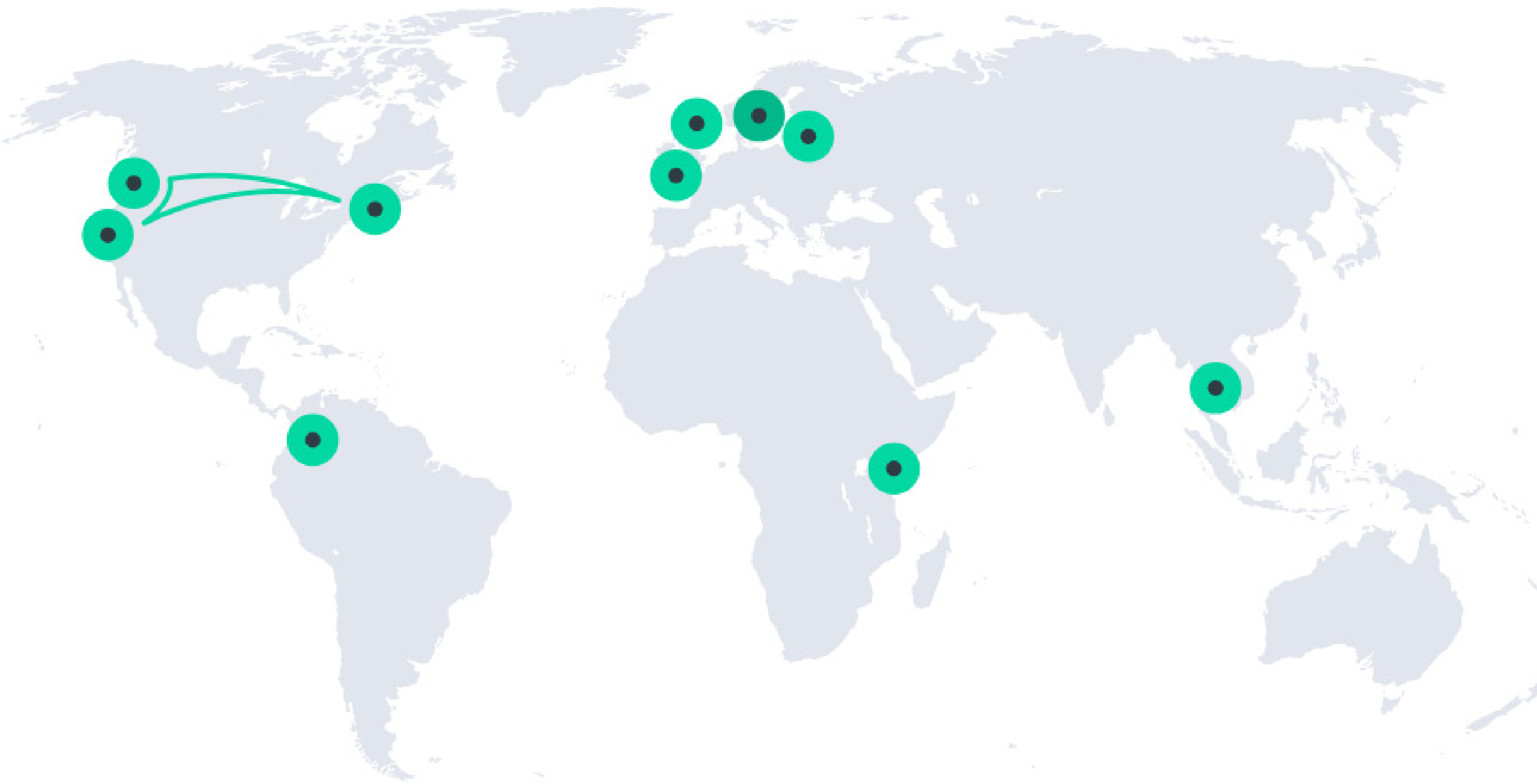

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About the Project

Applying the water-energy-food nexus to promote ecosystem-based adaptation in the Ewaso Ng'iro North Catchment, Kenya

This project seeks to support the Government of Kenya, five county governments (Laikipia, Samburu, Isiolo, Meru and Nyeri), local communities, and agro-based private enterprises to promote ecosystem-based adaptation practices and integrated planning for water, energy, agriculture and land use for resilient livelihoods in the Ewaso Ng'iro North Catchment Area.

The project seeks to apply ecosystem-based adaptation (EbA) and the nexus approaches to facilitate the co-production of resilient water-energy-food (WEF) knowledge with stakeholders (policymakers, local community groups, private sector, and non-governmental organizations) to inform decision and policymaking.

The project will contribute towards several development objectives which are in line with the Kenya Vision 2030 priorities, the Ewaso Ng'iro North Development Area (ENNDA) Integrated Regional Development Plan (2010-2040), the ENNDA catchment management strategy and the reformulation and implementation of CIDPs. These include increasing food security, especially pastoral livestock production; resilience through livelihoods diversification; employment creation through EbA solutions; agricultural growth; the conservation and safeguarding of critical habitats, including wildlife-protected areas and community wildlife conservancies. At the governance level, the nexus approach is expected to promote cooperation among actors and policy coherence across "policy silos", i.e. sectors, levels and scales and the key added value of the nexus approach is in integrating across the various plans and strategies, promoting synergies and generating co-benefits.

Expected results

- WEF nexus models and development scenarios for Ewaso Ng'iro North Catchment Area (ENNCA)
- Identification, validation, and promotion of innovative Ecosystem-based nexus solutions among key stakeholders in the ENNCA region
- Increased awareness of cross-sectoral interactions (water, energy, agriculture, and land) during the implementation, upscaling, out scaling, and transfer of ecosystem-based nexus solutions at the sub-national and national level

1. Introduction: A Basin Under Pressure

The Ewaso Ngiro North Basin represents one of Kenya's most critical yet stressed water systems. Originating from the glacial peaks of Mount Kenya and the Aberdare Ranges in the humid highlands of Nyeri and Nyandarua counties, the river flows 700 kilometers northeastward through Meru, Laikipia, Samburu, and Isiolo counties, passing through progressively drier landscapes before terminating in the Lorian Swamp near the Kenya-Somalia border. Along this journey, the basin supports 3.4 million people across five counties—Nyeri, Meru, Laikipia, Samburu, and Isiolo—each with distinct water demands, livelihood systems, and levels of access to this shared resource (Kiteme & Giesen, 2004).

The basin's dramatic climatic gradient creates fundamental disparities. Upper catchment areas in Nyeri County (southwestern Mount Kenya slopes) and Meru County (eastern Mount Kenya slopes) receive over 1,200 millimeters of rainfall annually on the mountain's humid zones, supporting intensive agriculture including coffee plantations around Nyeri town, tea estates in Kieni, and high-value horticultural exports in Timau and Meru North. The middle catchment across the Laikipia Plateau (1,600-2,300 meters elevation) experiences moderate rainfall of 400-750 millimeters supporting mixed farming around Nanyuki town, large-scale ranching across the plateau's rangelands, and wildlife conservancies in northern Laikipia. Lower catchment pastoral zones in Samburu County (centered around Maralal and Archer's Post) and Isiolo County (including Isiolo town and the Merti Plains) receive less than 300 millimeters annually and depend almost entirely on the Ewaso Ngiro River for livestock watering during critical dry seasons (Notter et al., 2007). This diversity, while ecologically rich, generates profound tensions over who gets water, when, and how much.

Agricultural uses dominate water demand across the basin, consuming 70-80% of total abstractions. Commercial farms in Laikipia County, particularly along the Burguret, Naro Moru, and Likii river corridors, cultivate wheat and horticultural crops for export markets while operating extensive dairy enterprises. Smallholder irrigation schemes in Meru County around Timau and along the Kathita tributary produce vegetables and food crops. In Nyeri County, irrigation supports coffee wet-processing and horticultural production around Nanyuki. Downstream, pastoral communities in Samburu's rangelands (from Archer's Post northward) and Isiolo's Merti and Sericho divisions depend on reliable water for livestock—the economic and cultural backbone of their societies. These competing demands, layered over climate variability and fragmented governance across five independent county governments, generate recurring conflicts that undermine the basin's long-term sustainability (WRA, 2021).

Water stress—the ratio of water withdrawals to available supply—provides a critical metric for assessing whether current patterns can be sustained. Previous studies have documented water scarcity challenges in specific sub-regions including the Burguret sub-catchment in Laikipia (Lanari et al., 2018) and the upper Ewaso reaches around Nanyuki (Mutiga et al., 2010), but comprehensive basin-wide assessment incorporating climate change projections and spatial differentiation across all five counties has remained limited. Understanding where stress is most acute, how it varies seasonally, and how climate change will reshape water availability is essential for developing equitable allocation policies and effective adaptation strategies.

2.

Modeling Water Stress: The WEAP Framework

To understand water stress comprehensively across the entire basin, this study employed the Water Evaluation and Planning system, a sophisticated modeling platform developed by the Stockholm Environment Institute. WEAP integrates the supply-side hydrology—how much water is available from rainfall, rivers, and groundwater—with demand-side requirements from cities, farms, livestock, industry, and ecosystems. This integration enables simulation of water allocation under various management strategies and climate scenarios (Sieber & Purkey, 2015; Yates et al., 2005).

The basin was divided into twelve sub-catchments based on tributary systems and administrative boundaries. Four upper catchment sub-basins capture the Burguret River (northwestern Mount Kenya), Naro Moru River (western slopes), Timau River (northeastern slopes draining Meru County), and other upper Ewaso tributaries in the Aberdares. Five middle catchment reaches represent the main Ewaso Ngiro stem flowing through Laikipia Plateau, the Likii tributary (northern Laikipia), the Nairobi River (southern Laikipia), and intermediate reaches approaching Samburu County. Three lower catchment zones extend from Archer's Post in southern Samburu through Isiolo County to the Lorian Swamp terminal zone. This spatial resolution enabled differentiated analysis of upstream-downstream dynamics central to water stress patterns.

Each sub-catchment was modeled with detailed soil moisture accounting, tracking how rainfall infiltrates, evaporates, supports vegetation, and eventually becomes streamflow or recharges groundwater. Different land uses—montane forests around Mount Kenya, croplands in Nyeri and Meru counties, rangelands across the Laikipia Plateau and Samburu lowlands, urban areas in Nanyuki and Isiolo—were assigned distinct hydrological characteristics reflecting their water consumption and runoff generation patterns.

Key WEAP soil moisture method parameters were calibrated for local conditions: root zone storage capacity ranged from 300-800 mm for montane forests to 150-400 mm for croplands and 100-250 mm for rangelands. Deep water storage capacity varied from 500-1500 mm depending on underlying geology, while runoff resistance factors (1.5-4.0) reflected slope gradients and soil infiltration characteristics across the twelve sub-catchments.

Thirty-five demand sites represented the basin's diverse water users across specific geographic locations. Five municipal water supply schemes serve urban populations in Nyeri town (population 136,000), Nanyuki (population 70,000), Isiolo town (population 78,000), Maralal in Samburu County (population 25,000), and Timau trading center in Meru County, with per capita demands varying by service level. Eighteen irrigation schemes were explicitly mapped, distinguishing twelve smallholder systems in Meru County (Timau, Mua, Kathita schemes totaling 8,400 hectares) and Nyeri County (Naro Moru, Burguret schemes totaling 7,200 hectares) from six large commercial operations in Laikipia County (including schemes along Burguret, Naro Moru, and main Ewaso stem totaling 14,800 hectares). Five livestock watering zones represented pastoral demand across Samburu's rangelands (Maralal, Baragoi, Wamba divisions), Isiolo's Merti and Sericho divisions, and northern Laikipia's pastoral areas. Industrial facilities including flower farms in Nanyuki and Timau, hotels around Mount Kenya, and processing plants were individually modeled. Environmental flow requirements at seven ecologically critical points, including the Burguret confluence, Nanyuki gauging station, Archer's Post (critical threshold for downstream ecology), and points along major tributaries—ensured that ecosystem needs were explicitly considered.

Environmental flow thresholds were established using a modified Tennant method calibrated to local hydrology, requiring minimum flows of 20% of mean annual flow during dry seasons (January-March, August-September) and 40% during wet seasons to maintain aquatic ecosystem integrity. These requirements, validated against observed ecological indicators and local stakeholder knowledge from participatory workshops, provide the basis for evaluating ecosystem impacts across all scenarios.

Supply infrastructure included twenty-eight surface water intake points distributed across the basin (eight in Nyeri County tributaries, six in Meru County tributaries, ten in Laikipia along main stem and tributaries, four in Samburu/Isiolo), forty-two groundwater boreholes with varying capacities concentrated in Laikipia Plateau aquifers and Isiolo's sedimentary formations, eight small storage dams and pans (including Nanyuki Municipal Dam and several ranch dams in Laikipia), and conveyance systems with realistic transmission losses. Groundwater was represented with scientifically based recharge estimates that vary by land cover: 10-18% of rainfall in forested areas around Mount Kenya and Aberdares, declining to just 3-8% in degraded rangelands of Samburu and Isiolo (WRMA, 2013).

Water allocation priorities followed Kenya's Water Act 2016 provisions, refined through stakeholder consultations across all five counties. Domestic and urban supply in Nanyuki, Isiolo, and other towns received highest priority, followed by livestock watering critical for Samburu and Isiolo pastoral economies, environmental flows particularly at Archer's Post and downstream reaches, irrigation demands concentrated in Laikipia and upper counties, and industrial uses. This hierarchy reflects legal frameworks while acknowledging that during severe scarcity, choices must be made about which demands take precedence.

The model was calibrated against streamflow observations from seven Water Resources Authority monitoring stations: Ewaso Ngiro at Archer's Post (station 1GB05, capturing cumulative basin flow), Ewaso Ngiro at Nanyuki (1GB03, middle catchment), Burguret River (1GA07, major tributary), Naro Moru River (1GA11), Timau River (1GA08, Meru County), and stations on Likii and Nairobi tributaries in Laikipia. Performance was rigorously evaluated using multiple statistical metrics spanning 2010-2018, achieving Nash-Sutcliffe Efficiency values exceeding 0.72 across all stations—meeting international standards for model reliability (Moriasi et al., 2007). Validation against independent data from 2019-2023 confirmed the model's predictive capability, providing confidence that scenario projections are grounded in demonstrated performance.

Additional performance metrics confirmed model robustness: percent bias (PBIAS) remained within ±15% and RSR (RMSE-observations standard deviation ratio) stayed below 0.60 across all stations. Station-specific performance ranged from NSE of 0.74 at Archer's Post (1GB05) to 0.81 at Burguret River (1GA07), with the highest accuracy in upper catchment tributaries where flow regimes are more predictable.

3. Climate Change: Reshaping Water Availability Across the Basin

Climate projections were derived from five state-of-the-art General Circulation Models contributing to the Coupled Model Intercomparison Project Phase 6, the scientific foundation for the IPCC's Sixth Assessment Report. Two emissions pathways were analyzed: SSP2-4.5 representing moderate mitigation efforts, and SSP5-8.5 representing high emissions with limited climate action (O'Neill et al., 2016; Riahi et al., 2017; IPCC, 2021).

Under the moderate emissions pathway, the median scenario projects that annual renewable water resources will decline by 8-14% across the basin by mid-century, with differential impacts by region. Upper catchment areas in Nyeri and Meru counties may experience modest declines of 6-10% as higher elevation zones partially buffer temperature increases. Middle catchment Laikipia Plateau faces steeper declines of 10-15% as its semi-arid conditions amplify evaporative losses from 1.6°C temperature increases. Lower catchment Samburu and Isiolo counties face the most severe impacts with 12-18% declines in renewable water, driven by both reduced rainfall (particularly during critical dry seasons) and elevated evapotranspiration in their already arid conditions.

However, substantial uncertainty exists across sub-regions. The wet scenario suggests that Nyeri and Meru highland zones might actually see 2-5% increases in water availability through enhanced orographic rainfall on Mount Kenya slopes, while Laikipia could maintain near-current levels. The dry scenario indicates severe reductions: 15-20% in Nyeri/Meru, 18-24% across Laikipia, and catastrophic 22-28% declines in Samburu/Isiolo regions.

Critically, all scenarios agree on several troubling trends across the entire basin regardless of total precipitation changes. Intra-seasonal rainfall variability increases by 8-12%, meaning rainfall becomes more erratic with longer dry spells interspersed with intense storms—patterns that stress rainfed agriculture in Nyeri and Meru while devastating pastoral systems in Samburu and Isiolo that depend on predictable seasonal patterns. Drought frequency accelerates from once every five years historically to once every three years by mid-century across all five counties.

Dry season flows show particularly concerning declines critical for downstream areas. The Ewaso Ngiro at Archer's Post—the critical threshold where flows either continue to Samburu/Isiolo or fail completely—will experience 12-18% flow reductions during January-March and August-September dry seasons under median projections, 8-12% under wet scenarios, or 22-32% under dry scenarios. Upstream tributaries like Burguret and Naro Moru in Laikipia show similar or steeper declines (15-25% median scenario), directly impacting irrigation schemes dependent on these sources (Osima et al., 2018; Gebrechorkos et al., 2019).

Groundwater recharge patterns follow similar spatial differentiation. Highland aquifer recharge zones around Mount Kenya in Nyeri County and the Aberdares may maintain 92-96% of current recharge rates under median scenarios due to sustained forest cover and higher rainfall. Laikipia Plateau aquifers face 8-14% recharge reductions, exacerbating current over-pumping by commercial farms and Nanyuki town. Samburu and Isiolo aquifers, already stressed, face 16-24% recharge declines under dry scenarios, threatening the borehole systems that provide critical drought buffers for pastoral communities.

4.

Current Water Stress: A Basin Divided by Geography

Under current conditions, total water demand across the basin reaches 325 million cubic meters annually. Irrigation dominates at 67% of total demand, concentrated in Laikipia County (128 million cubic meters, representing 39% of basin-wide irrigation), followed by Meru County (52 million cubic meters, 16%), and Nyeri County (38 million cubic meters, 12%). Domestic uses account for 16%, led by Nanyuki town in Laikipia (18 million cubic meters), Isiolo town (12 million cubic meters), and rural domestic supply across Samburu County (15 million cubic meters). Livestock watering consumes 10%, predominantly in Samburu (18 million cubic meters) and Isiolo (12 million cubic meters) where pastoralism dominates. Industrial and commercial uses total 4%, concentrated around Nanyuki (flower farms, hotels) and Timau (horticulture processing). Environmental flows theoretically require 3% but receive far less.

Available renewable supply averages 410 million cubic meters annually, but exhibits profound spatial inequality in generation and access. Upper catchment Nyeri and Meru counties generate approximately 165 million cubic meters (40% of total basin supply) from Mount Kenya tributaries including Burguret (35 Mm^3), Naro Moru (32 Mm^3), Timau (28 Mm^3), and smaller streams. These counties abstract only 95 million cubic meters, leaving 70 Mm^3 flowing downstream. Laikipia County in the middle catchment generates an additional 115 million cubic meters from its portion of the main stem and tributaries, but abstracts 128 million cubic meters—a deficit met through upstream flows and groundwater overdraft. Samburu and Isiolo counties generate only 62 million cubic meters from local tributaries and seasonal streams, yet require 74 million cubic meters, depending entirely on flows from upstream counties that increasingly fail during dry seasons.

This spatial imbalance generates dramatically different water stress levels across counties. Upstream Nyeri County exhibits moderate stress with a water stress index of 35%, as abstractions (45 Mm^3) remain well below local generation (128 Mm^3) supplemented by pristine Mount Kenya sources. Meru County shows similar moderate stress at 38%, with abstractions (58 Mm^3) sustainable against generation (152 Mm^3). Laikipia County in the transition zone experiences medium-high stress at 55%, reflecting substantial commercial agricultural demand (128 Mm^3) against moderate supply (116 Mm^3 local generation plus upstream contributions). Downstream Samburu County faces severe stress reaching 72%, as demand (42 Mm^3) substantially exceeds what reaches this region after upstream abstractions. Isiolo County experiences catastrophic stress exceeding 85% even during average years, with demand (32 Mm^3) far outstripping the residual flows and limited groundwater available (Falkenmark & Widstrand, 1992).

During drought years such as 2017 and 2022, these disparities intensify dramatically. The Ewaso Ngiro at Archer's Post—the gateway to Samburu and Isiolo counties—experienced zero flow for 4-6 consecutive months, forcing complete reliance on diminishing groundwater. Samburu's water stress exceeded 95%, with livestock mortality reaching 35% in Baragoi and Wamba divisions. Isiolo County faced near-total supply failure with stress indices above 98%, triggering humanitarian interventions in Merti and Sericho divisions. Even Laikipia experienced stress levels reaching 72% as Nanyuki town implemented rationing and commercial farms along Burguret and Naro Moru rivers depleted flows to zero locally.

Seasonal patterns reveal even more acute stress during critical dry periods from January through March and August through September. During these months, unmet water demand averages 45 million cubic meters annually. Isiolo County experiences 42% of its dry season demand going unmet, with Isiolo town facing severe rationing and pastoral areas around Merti accessing water only from emergency trucking. Samburu County faces 35% unmet demand, forcing pastoralists in Maralal and Baragoi divisions to trek 15-30 kilometers to functional boreholes. Laikipia County sees 18% deficits concentrated in northern pastoral zones and affecting Nanyuki's industrial sector. Environmental flow requirements fare worst of all, being met only 33% of the time at Archer's Post and downstream monitoring points, indicating severe ecosystem degradation in the lower Ewaso Ngiro reaches through Samburu and Isiolo.

WEAP's demand site reliability metric quantifies water security more precisely: Isiolo town achieves only 58% reliability (percentage of time demand is fully met), meaning residents face supply shortages nearly half the year. Pastoral demand sites around Merti and Sericho divisions show even lower reliability at 45%, while Nanyuki achieves 82% reliability and upper catchment towns in Nyeri and Meru maintain 90-95% reliability—illustrating the stark upstream-downstream disparity in water security.

This upstream-downstream gradient reflects both hydrological reality and governance failure. Upper catchment users in Nyeri and Meru counties abstract water close to sources before it flows downstream. Laikipia's commercial farms capture flows along the main stem and major tributaries. But the problem is compounded by weak monitoring and enforcement. Evidence suggests that actual abstractions in Laikipia County may exceed allocated permits by 30-50%, a finding consistent with previous research (Lanari et al., 2018). Major irrigation schemes along Burguret, Naro Moru, and Likii rivers abstract water without functioning meters, making violations undetectable. When permits are routinely violated and monitoring is inadequate, allocation planning becomes meaningless, and downstream users in Samburu and Isiolo suffer the consequences.

5. Future Trajectories

5.1 Business-as-Usual Leads to Regional Crisis

Projecting current trends forward under a business-as-usual scenario reveals deeply unsustainable trajectories with differential impacts across the basin's five counties. By 2045, unmet water demand escalates to 78 million cubic meters annually, representing 24% of total demand going unsatisfied. This nearly triples the current deficit and transforms episodic stress into chronic crisis, but the burden falls unevenly across regions.

Downstream counties bear the catastrophic brunt. Isiolo County's dry season unmet demand reaches 47%, meaning that during half the year, nearly half of all water needs cannot be met from available sources. Isiolo town faces supply availability only 3-4 days per week. Pastoral areas in Merti, Sericho, and approaching Lorian Swamp experience complete surface water failure, depending entirely on diminishing groundwater that models project will deplete in critical boreholes within 15-25 years at current extraction rates. Samburu County faces 40% dry season deficits, with Maralal town implementing permanent rationing and pastoral divisions (Baragoi, Wamba, South Horr) accessing water only through emergency measures. The Ewaso Ngiro at Archer's Post—the lifeline for these downstream counties—flows only 4-5 months per year compared to 8-9 months historically.

Middle catchment Laikipia County experiences intensifying stress reaching 68% (up from current 55%), with Nanyuki town requiring new water sources and commercial agricultural schemes along Burguret and Naro Moru rivers facing 25-30% production reductions from water scarcity. Northern Laikipia pastoral areas merge into Samburu's crisis conditions. Even upper catchment counties face emerging challenges. Nyeri County's stress index climbs from 35% to 48% as population growth in Nyeri town and expansion of peri-urban irrigation around Naro Moru outpace sustainable yields. Meru County rises from 38% to 52% stress as Timau area irrigation expansion and Meru town growth strain the Kathita and Timau tributary systems.

Environmental flows collapse across the basin. Compliance drops to just 15% at Archer's Post, essentially abandoning ecosystem protection in Samburu and Isiolo reaches where the river becomes an extraction channel rather than a living ecosystem. Middle reaches in Laikipia see environmental flow provision decline to 25%, degrading aquatic habitat and reducing dry-season baseflow contributions. Even upper tributaries in Nyeri and Meru counties achieve only 40-50% compliance as every drop is captured for human uses.

Several factors drive this regional deterioration. Population growth continues at over 2% annually in Isiolo (2.8%), Samburu (2.5%), and Laikipia (2.3%), slower but substantial in Nyeri (1.8%) and Meru (2.1%), collectively adding 1.8 million people to the basin by mid-century. Agricultural expansion proceeds most aggressively in Laikipia (projected 22% irrigation area increase) and upper Meru County (18% increase) in response to food security imperatives and market opportunities. Climate change reduces dry season availability most severely in downstream Samburu and Isiolo (25-32% declines) while moderately affecting Laikipia (15-20%) and minimally impacting upper Nyeri and Meru (8-12%).

Groundwater depletion accelerates unevenly. Laikipia Plateau aquifers face critical depletion at 1.5-1.8 meters per year (compared to current 0.8-1.2 m/year), threatening Nanyuki's water supply and numerous commercial farms within 20-30 years. Isiolo's sedimentary aquifers approach depletion even faster at 2.0-2.5 m/year due to drought-driven over-pumping, with 40% of boreholes projected to fail by 2040. Samburu's fractured rock aquifers show localized severe depletion around Maralal (1.8 m/year) and Baragoi (2.2 m/year). Upper catchment Nyeri and Meru aquifers remain relatively stable (0.3-0.5 m/year depletion) due to better recharge in forested zones, but peri-urban areas around Nyeri town show emerging stress (0.8 m/year).

6. Pathways to Sustainability: Regional Solutions for an Integrated Basin

The WEAP scenario analysis framework explored six alternative futures beyond the Baseline: County Focus (each county optimizing independently), Water and Agricultural Improvements (irrigation efficiency and water harvesting), Energy and Climate Change (renewable energy integration with climate adaptation), Cooperation (coordinated multi-county allocation), and Ecosystem Restoration (comprehensive nature-based solutions). The three most impactful scenarios—Green Infrastructure, Technology Intensification, and Integrated Nexus—are detailed below.

The modeling explored three alternative scenarios beyond business-as-usual, each with spatially differentiated interventions across the basin's diverse regions. The Green Infrastructure scenario focused on ecosystem-based adaptation: riparian restoration along 500 kilometers prioritizing Burguret, Naro Moru, Timau, and main Ewaso stem reaches through Laikipia and Samburu; agroforestry expansion across 45,000 hectares concentrated in Meru County (18,000 ha), Nyeri County (12,000 ha), and southern Laikipia (15,000 ha); and soil conservation measures covering 80,000 hectares targeting degraded areas across all counties but emphasizing Samburu (35,000 ha) and Isiolo (25,000 ha) rangelands. The Technology Intensification scenario emphasized efficiency improvements: increasing irrigation efficiency by 25% across Laikipia schemes (8,400 ha converted to drip/sprinkler), Meru smallholder schemes (5,200 ha), and Nyeri peri-urban areas (4,800 ha); deploying solar water pumping in off-grid pastoral areas (850 systems across Samburu and Isiolo); and promoting climate-smart agriculture particularly in Meru and Nyeri food production zones. The Integrated Nexus scenario combined both approaches with coordinated basin-wide governance reforms.

The Technology Intensification and Integrated Nexus scenarios also incorporated small-scale hydropower development at five identified sites: two along the Burguret River (150 kW combined capacity), one on the Naro Moru tributary (80 kW), and two on upper Ewaso tributaries (200 kW combined). These installations, designed with fish-friendly intakes and environmental flow bypasses, provide rural electrification to support solar pumping systems while maintaining downstream ecological connectivity.

The Integrated Nexus scenario demonstrates that catastrophic regional outcomes are not inevitable. By 2045, this comprehensive approach reduces unmet water demand from 24% under business-as-usual to just 6% of total requirements—a four-fold improvement achieving near-sustainability across the basin. But benefits vary by region, reflecting targeted interventions.

Downstream counties benefit most dramatically from integrated interventions. Samburu County's livestock water deficits reduce by 48% compared to business-as-usual, achieved through: ecosystem restoration in upper catchment Nyeri and Meru counties increasing baseflow reaching Samburu by 12-15%; irrigation efficiency in Laikipia freeing 18 million cubic meters annually that flows downstream; and strategic borehole development with solar pumping in Maralal, Baragoi, and Wamba divisions providing drought buffers. The Ewaso Ngiro at Archer's Post maintains flow 9-10 months annually (compared to 4-5 months under business-as-usual), restoring reliability for downstream users.

Isiolo County's agricultural deficits cut by 42%, through similar mechanisms plus targeted small-scale irrigation development (1,800 ha) along the Isiolo town corridor and Merti area using solar pumping and efficient drip systems. Isiolo town's domestic supply stabilizes with 95% reliability (compared to 60% under business-as-usual). Pastoral areas in Sericho and Garbatulla divisions gain access to properly-managed borehole clusters reducing trekking distances from 15-30 km to <5 km during dry seasons.

Middle catchment Laikipia County achieves water stress reduction from 68% (business-as-usual) to 42% through irrigation efficiency on 8,400 hectares of commercial farms along Burguret, Naro Moru, and Likii tributaries. This efficiency transformation saves 22 million cubic meters annually—16 Mm^3 reallocated downstream to Samburu and Isiolo, 6 Mm^3 supporting Nanyuki town's growth and northern Laikipia pastoral zones. Nanyuki's water supply achieves 98% reliability with reduced groundwater dependence as surface allocations improve.

Upper catchment Nyeri and Meru counties maintain their moderate stress levels (35-42%) while substantially contributing to basin-wide improvements through ecosystem restoration. Nyeri County's riparian restoration along 120 kilometers of Burguret and Naro Moru tributaries increases dry-season baseflow 8-12%, benefiting all downstream users. Meru County's 18,000 hectares of agroforestry in Timau and Meru North areas enhances infiltration, reducing flashy runoff while increasing groundwater recharge that sustains dry-season flows. These upper catchment interventions generate 85% of total ecosystem restoration benefits despite receiving only 35% of direct water security gains—a spatial imbalance addressed through benefit-sharing mechanisms where downstream counties (Samburu, Isiolo, Laikipia) contribute to Payment for Ecosystem Services funds compensating Nyeri and Meru conservation activities.

Environmental flows see 67% improvement in provision across the basin. Compliance at Archer's Post increases from 15% (business-as-usual) to 50%, supporting aquatic ecosystem recovery in Samburu and Isiolo reaches. Middle Laikipia reaches achieve 60% compliance (from 25%), and upper tributaries in Nyeri and Meru reach 75% compliance (from 40-50%). While still imperfect, this represents substantial ecosystem protection compared to near-complete abandonment under business-as-usual.

Groundwater stabilization varies regionally but improves dramatically across critical zones. Laikipia Plateau aquifers stabilize at 0.2 m/year depletion (compared to 1.5-1.8 m/year business-as-usual) through irrigation efficiency reducing pumping demand and enhanced recharge from soil conservation. Isiolo aquifers achieve 0.4 m/year depletion (compared to 2.0-2.5 m/year), extending viability from 15-20 years to 50+ years through managed abstraction and recharge enhancement. Samburu's critical boreholes around Maralal and Baragoi stabilize at 0.3 m/year (from 1.8-2.2 m/year). Upper catchment Nyeri and Meru aquifers approach equilibrium at 0.05-0.1 m/year depletion through forest protection enhancing recharge.

Implications for Policy and Practice Across Counties

These findings carry several important implications for water resource management differentiated by the basin's five counties and similar transboundary systems globally;

First and most fundamentally, county-isolated planning must give way to **basin-wide coordination.** When Nyeri, Meru, Laikipia, Samburu, and Isiolo county governments plan water development independently without accounting for upstream-downstream dependencies, the inevitable result is overallocation, conflicts, and downstream suffering. Strengthening the Ewaso Ngiro North Catchment Area Water Resources Authority as a coordinating body with real authority to mediate allocation across county boundaries represents a non-negotiable prerequisite for sustainable management.

Second, **climate adaptation investments** should prioritize ecosystem-based approaches in upper catchment areas, particularly Nyeri and Meru counties. The modeling demonstrates that riparian restoration along Mount Kenya tributaries (Burguret, Naro Moru, Timau) and sustainable land management in these humid highlands maintain and even enhance baseflows that are critical for all downstream users through Laikipia, Samburu, and Isiolo. However, Nyeri and Meru bear conservation costs while downstream counties capture benefits, requiring benefit-sharing mechanisms where Laikipia's commercial agriculture sector, Samburu's pastoral economy, and Isiolo County contribute to Payment for Ecosystem Services funds compensating Nyeri and Meru conservation.

Third, **water use efficiency programs** must be strategically targeted by region. Laikipia County's commercial irrigation schemes along Burguret, Naro Moru, and Likii tributaries represent the highest-priority efficiency investments, as these abstract 128 million cubic meters annually—39% of basin-wide irrigation demand—yet operate at only 48-58% efficiency. Converting 8,400 hectares to drip irrigation saves 22 million cubic meters annually, enough to meet Samburu County's entire livestock water requirement or Isiolo County's combined domestic and pastoral needs. However, efficiency gains must be coupled with allocation agreements ensuring saved water flows downstream rather than enabling Laikipia agricultural expansion. Meru and Nyeri county smallholder schemes represent secondary efficiency priorities (5,200 ha and 4,800 ha respectively), generating smaller absolute savings (8-12 Mm^3 combined) but important for local water security around Timau, Meru town, and Nanyuki.

Fourth, **groundwater development** in pastoral areas of Samburu and Isiolo counties should be guided by rigorous sustainable yield assessments to prevent aquifer depletion. While boreholes provide critical drought resilience for pastoral communities in Maralal, Baragoi, Wamba (Samburu), and Merti, Sericho, Garbatulla (Isiolo), unregulated development has created over-extraction hotspots where depletion rates exceed 1.2-2.5 meters per year. Strategic placement of properly-managed water points, informed by hydrogeological surveys of Samburu's fractured basement aquifers and Isiolo's sedimentary formations, coupled with solar pumping enabling cost-effective operation and monitoring systems tracking water levels, can provide pastoral water security without undermining the resource base.

Fifth, **climate change** must be explicitly incorporated into all five counties' water resource planning processes. County water master plans that fail to account for projected declines in dry season flows—particularly severe in downstream Samburu and Isiolo (25-32% declines) but also significant in Laikipia (15-20%) and moderate in Nyeri and Meru (8-12%)—systematically underestimate future stress. Basin-scale integrated modeling, as demonstrated in this study, reveals vulnerabilities invisible when Laikipia plans irrigation expansion without considering upstream Nyeri/Meru generation declines or downstream Samburu/Isiolo impacts (Gerlak et al., 2018).

8. Looking Ahead: From Regional Crisis to Basin-Wide Sustainability

The stark contrast between business-as-usual and integrated intervention scenarios reveals both the challenge and the opportunity facing the Ewaso Ngiro North Basin's five counties. Business-as-usual leads inexorably toward crisis: catastrophic deficits in Samburu and Isiolo counties where 40-47% of dry season demand goes unmet, severe stress in Laikipia reaching 68%, mounting pressure in previously-secure Nyeri and Meru climbing to 48-52%, mounting conflicts as upstream abstractions strangle downstream flows, ecosystem collapse as the Ewaso Ngiro through Archer's Post flows only 4-5 months annually, and erosion of livelihoods for 3.4 million people across the basin. This trajectory is not inevitable but represents the cumulative consequence of fragmented governance across five independent county governments, inadequate monitoring at critical points (Archer's Post, Nanyuki, tributary junctions), uncoordinated development where Laikipia expands irrigation without downstream consultation, and failure to adapt to changing climate realities affecting all counties but most severely Samburu and Isiolo.

The integrated nexus scenario demonstrates an alternative pathway achievable through coordinated action across all five counties. Through ecosystem restoration in upper Nyeri and Meru counties enhancing natural water regulation for the entire basin, technological improvements in middle Laikipia using water more efficiently and freeing flows for downstream counties, strategic infrastructure in lower Samburu and Isiolo providing drought buffers, and governance reforms coordinating these actions across county boundaries, the basin can achieve near-sustainability even under climate change pressures. Unmet demand falls from 24% basin-wide to just 6%, with particularly dramatic improvements in downstream Samburu (48% deficit reduction) and Isiolo (42% deficit reduction). Environmental flows improve 67%, ensuring the Ewaso Ngiro through Archer's Post maintains 9-10 months annual flow supporting aquatic ecosystems in Samburu and Isiolo. Groundwater stabilizes across critical zones in Laikipia Plateau, Isiolo sedimentary aquifers, and Samburu's fractured rock systems.

Realizing this alternative pathway requires sustained commitment differentiated by county context. Nyeri and Meru counties must invest in riparian restoration along Mount Kenya tributaries (Burguret, Naro Moru, Timau) and enforce forest protection in Aberdares and mountain zones, supported by benefit-sharing mechanisms compensating conservation costs. Laikipia County must implement irrigation efficiency across commercial schemes and couple improvements with allocation agreements ensuring saved water benefits downstream rather than enabling local expansion. Samburu and Isiolo counties must develop strategic borehole networks with proper management avoiding over-extraction while advocating for equitable allocation protecting downstream rights. All five counties must strengthen monitoring infrastructure at critical points (Archer's

Post threshold, Nanyuki junction, tributary confluences), build capacity for water resource professionals enabling evidence-based planning, and engage stakeholders across the upstream-downstream divide in collaborative decision-making.

The modeling framework itself represents a valuable tool for ongoing adaptive management across this complex multi-county basin. As conditions change—whether through climate shifts affecting Mount Kenya glaciers and Aberdares rainfall, population movements between Nyeri's peri-urban areas and Samburu's pastoral zones, economic development in Isiolo's LAPSSET corridor, or policy reforms coordinating the five county governments—the WEAP model can be updated to evaluate emerging challenges and assess potential responses. This enables water management to evolve from reactive crisis response (humanitarian interventions when Archer's Post runs dry, emergency rationing in Nanyuki, trucking water to Samburu boreholes) toward proactive strategic planning guided by quantitative evidence of basin-wide interactions rather than county-isolated decisions.

The Ewaso Ngiro North Basin—from Mount Kenya's glacial sources through Nyeri and Meru's productive highlands, across Laikipia's contested plateau, to Samburu and Isiolo's fragile drylands—stands at a crossroads. One path leads to deepening crisis: water wars between upstream commercial farmers and downstream pastoralists, ecological collapse of the Ewaso Ngiro through its lower reaches, economic devastation in Samburu and Isiolo, and mounting pressure even in previously-secure Nyeri and Meru. The other leads to sustainable management: equitable allocation protecting downstream rights while maintaining upstream productivity, ecological restoration supporting the entire basin, and resilience against climate change through coordinated adaptation across all five counties. The modeling presented here demonstrates that the sustainable path is technically feasible and economically viable through targeted interventions optimized for each region's context. The question is whether the political will can be mobilized to coordinate across county boundaries, whether Laikipia's commercial agriculture will accept efficiency coupled with downstream obligations, whether Nyeri and Meru will invest in ecosystem conservation benefiting others, and whether Samburu and Isiolo will gain the voice and legal standing to defend their rights. For the 3.4 million people who depend on this basin—from Nyeri's coffee farmers to Nanyuki's urban residents, from Laikipia's wheat producers to Samburu's pastoralists, from Meru's horticulturalists to Isiolo's emerging town—the answer to this question will determine whether water becomes a foundation for shared prosperity or a source of escalating conflict and suffering.

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