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Technical Report

Ecological Functions, Ecosystem Services and Water Management Challenges of the Omo-Gibe River Basin, Ethiopia

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Back cover photo: Upper catchment of the Omo-Gibe River, Ethiopia (*Photo*: Wolde Mekuria/IWMI)

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Acronyms and abbreviations

ADLI	Agricultural Development-Led Industrialization
AET	Actual evapotranspiration
AfDB	African Development Bank
ATTZ	Aquatic-Terrestrial Transition Zone
BAO	Basin Administration Office
BCM	Billion cubic meters
BOD_5	Biochemical oxygen demand over five days
BRIGHT	Basin Management Support for Resilient, Inclusive Growth and Harmonized Transformation for the National IWRMP of Ethiopia
CMIP6	Coupled Model Intercomparison Project Phase 6
CPUE	Catch per unit effort
CRGE	Climate-Resilient Green Economy
DAFNE	Decision Analytic Framework to explore the water-energy-food Nexus
DSOCR	Desired State of Conservation for Removal
EEP	Ethiopian Electric Power
E-flow	Environmental flow
EIA	Environmental Impact Assessment
EIB	European Investment Bank
ENSO	El Niño-Southern Oscillation
ESIA	Environmental and Social Impact Assessment
ESIR	Environmental and Social Impact Review
ESMP	Environmental and Social Management Plan
GDP	Gross domestic product
GRACE	Gravity Recovery and Climate Experiment
GTP	Growth and Transformation Plan
HBV	Hydrologiska Byråns Vattenbalansavdelning hydrological model
ITCZ	Intertropical Convergence Zone
IWRM	Integrated Water Resources Management
IWRMP	Integrated Water Resources Management Plan
JSTOR	Journal Storage
KSDP	Kuraz Sugar Development Project
LAPSSET	Lamu Port-South Sudan-Ethiopia Transport Corridor
LLJ	Low-level jet
LULC	Land use / land cover
MW	Megawatt
NASA	National Aeronautics and Space Administration
NGO	Non-governmental organization
PASDEP	Plan for Accelerated and Sustained Development to End Poverty
RCP	Representative Concentration Pathway
RMSE	Root mean square error
SDG	Sustainable Development Goal
SDPRP	Sustainable Development and Poverty Reduction Program
SEA	Strategic Environmental Assessment
SSP	Shared Socioeconomic Pathway
SWAT	Soil and Water Assessment Tool

TDS	Total dissolved solids
TS	Topic search
TWS	Terrestrial water storage
UNESCO	United Nations Educational, Scientific and Cultural Organization
USDA	United States Department of Agriculture

1. Introduction

Ethiopia has a central highland mass bisected by the Great Rift Valley, creating a radial drainage network with 12 major basins: eight river basins, one lake basin, and three dry basins with no surface outflow (Abbate et al. 2015; Berhanu et al. 2014). The country generates 124.4 Bm^3/year of river water (Berhanu et al. 2014). Approximately 80–90% of Ethiopia's total water resources and 82.8% of its surface runoff are concentrated in four major basins—the Abbay, Baro-Akobo, Omo-Gibe, and Tekeze—which host 30–40% of the population (Wassie 2020). Ethiopia's basins face converging pressures from climate change, population growth, and weak governance. These pressures manifest as surface-water stress, most critically in the Awash River Basin because of industrial discharge and irrigation and in the Omo-Gibe Basin because of agricultural runoff (Awoke et al. 2016), and as groundwater stress, most critically in the Rift Valley Lakes Basin (Water and Land Resource Centre 2024a).

Endorheic basins lack surface outflows to the marine environment and therefore retain most inflowing sediments and dissolved materials within their boundaries. When basin-wide precipitation exceeds evaporative losses, terminal lakes form in their depocenters and tend toward saline geochemistry because dissolved materials accumulate and become concentrated through evaporation (Nichols 2007; Yapiyev et al. 2017). These lakes are highly vulnerable to upstream changes because they lack downstream buffering, as illustrated by the collapse of the Aral Sea (Yapiyev et al. 2017). Although endorheic basins cover 25% of the global continental area, they generate only 1.9% of global runoff because they occur predominantly in arid and semiarid regions (Dürr et al. 2011). In arid regions, these basins are vital to the water–ecosystem–agriculture nexus (Sun et al. 2018; Yapiyev et al. 2017).

Among endorheic basins, the Omo-Gibe Basin stands out for its notable climatic gradient (Dondeyne et al. 2024), which makes upstream changes especially susceptible to cascading downstream effects. Because of transformations in the hydraulic regime, the basin illustrates broader Sustainable Development Goal (SDG) trade-offs: the same infrastructure that delivers "clean" energy and export earnings, that has been associated with electrification, employment and local economic gains (Kedanemariam and Mishra 2013), and that provides more regular dry-season flows and a degree of attenuation of extreme floods, also alters the ecological functions that support food, water, and biodiversity. These outcomes are treated here as trade-offs that are distributed unevenly between groups and between reaches of the basin, rather than as uniformly positive or negative.

Studes predicted almost opposing impacts of the future Gibe III reservoir on Lake Turkana's water level. Studies that were published prior to 2020 anticipated a water level decline and surface area recession in Lake Turkana's water level (Avery and Tebbs 2018; Human Rights Watch 2017). — a projected decline specific to the pre-2020 literature, distinct from the post-2020 observed expansion discussed below. The commissioning of Koysha (Gibe IV) is projected to regulate Lake Turkana's levels further, with a regulated seasonal amplitude of approximately 0.3 m specified in the Koysha Environmental and Social Impact Assessment (Ethiopian Electric Power 2016a). The project's basic design study, by contrast, concludes that Koysha's incremental effect on the lake will be minimal (Studio Pietrangeli 2016). Calculations based on bathymetric mapping and USDA/NASA G-REALM satellite altimetry predict that this dampening would be strongly correlated (R^2=0.86) with a reduction in the Aquatic-Terrestrial Transition Zone (ATTZ), the portion of the littoral zone that alternates between wet and dry conditions in response to seasonal fluctuations (Gownaris et al. 2017). This correlation reflects lake bathymetry: for a given volume of seasonal inflow, a larger lake surface area produces a proportionally smaller vertical level change, so the degree of dampening depends on basin topography rather than being an inflow-independent property of expansion itself. Global research identifies the ATTZ as a vital driver of lake productivity: it facilitates the accumulation and resuspension of organic matter during seasonal flood cycles, accelerates biogenic nutrient recycling, and provides spawning, nursery, and refuge habitats and breeding cues for fish (Gasith and Gafny 1990; Junk et al. 1989; Kolding and van Zwieten 2012; Lamberts and Koponen 2008; Wantzen et al. 2008). A projected contraction of the ATTZ may therefore contribute to the decline in chlorophyll-a concentrations modeled by Tebbs et al. (2020), with implications for the lake's aquatic food web and, ultimately, fisheries productivity and yield. Lake Turkana's fisheries provide vital alternative sustenance for lakeshore communities, where roughly 75% of the growing population supplements its diet through food aid (Gownaris et al.2017). Overall, the dam has probably reduced variability but not necessarily impacted on the overall water level).

Studies published since 2020 have reported an expansion of Lake Turkana, in contrast to the earlier predictions. Dondeyne et al. (2024) report that the lake has risen by about 4-5 m over the past 15 years, with an associated expansion in lake area. Similarly, Byrne et al. (2024) reported substantial increases in the lake's surface area and volume between 2000 and 2023. Lake level rise is primarily attributed to increasing rainfall and land use change. Flooding has also been reported in communities in the Dassanech District of Ethiopia, which lies at the downstream end of the lower Omo on the delta, while competition among fishers is reported to have intensified (Trenchard 2026). The available sources such as OCHA/IOM/VSF-G (2024) attribute this flooding to Omo River overflow and to sudden releases from Gibe III rather than to lake-level rise, and the extent to which a backwater effect from the rising lake propagates upstream into this reach has not been established.

These transformations intersect with several Sustainable Development Goals (SDGs), most directly SDG 6 (clean water and sanitation), SDG 13 (climate action) and SDG 15 (life on land), and indirectly SDG 2 (zero hunger) and SDG 7 (affordable and clean energy). SDG 14 (life below water) is used here by extension rather than by definition: its agreed formulation concerns the oceans, seas and marine resources (United Nations 2015), and it is not assessed for landlocked countries in the SDG Index (Sachs et al. 2026). Ethiopia's third Voluntary National Review nonetheless reports SDG 14 through inland freshwater indicators, including inland fish production and the area of lakes, rivers and wetlands under formal protection (Ministry of Planning and Development 2025). The inland-water dimensions relevant here fall formally under targets 6.6 and 15.1; where SDG 14 is invoked below, it is therefore applied, consistent with national practice, as an analogue for aquatic productivity and fisheries.

Global progress towards the SDGs is uneven and, in aggregate, off track. The tenth annual United Nations stock take finds that only about 18% of targets are on track or already met, 17% show moderate progress, close to half are advancing too slowly, and nearly one fifth have regressed relative to the 2015 baseline (UN DESA 2025). Gains have been clearest in areas such as electricity access, whereas biodiversity- and ecosystem-related targets under SDG 14 and SDG 15 show stagnation or reversal. Climate action likewise lags the trajectory implied by the Paris Agreement: full implementation of currently submitted nationally determined contributions is projected to result in warming of 2.3-2.5 °C over this century, and current policies in up to 2.8 °C (UNEP 2025).

Ethiopia's own SDG self-assessment broadly corroborates this uneven picture. Of the 158 indicators for which recent data were available, the third Voluntary National Review reports 21% as achieved and 42% as on track, with 7% requiring accelerated effort and 30% off track (Ministry of Planning and Development 2025). Hydropower-led expansion has produced measurable gains under SDG 7, where all five reported indicators are on track: electricity access rose from 21.8% in 2015/16 to 63% in 2021/22, connected households from 2.50 to 8.83 million by 2023/24, and 97.9% of generation in 2023/24 came from renewable sources, although roughly one third of the population still lacks access and continued reliance on traditional biomass qualifies this progress (Section 1.4; Ministry of Water and Energy et al. 2025). Reported access levels differ across sources, reflecting differences in reference year and in the definition of access (United Nations in Ethiopia 2025). Water and food security perform less well. Half of the six SDG 6 indicators require accelerated effort and a further 16.7% are off track: safely managed drinking water reached 74% in 2021/22 against a milestone of 79.5%, safely managed sanitation 26% against 52%, and access to a handwashing facility with soap and water stood at 13%; stricter international monitoring reports 14% of the population using a safely managed drinking-water service and withdrawal of 32% of renewable water resources once environmental flow requirements are taken into account (UN-Water 2025). Under SDG 2, 60% of indicators are off track, with undernourishment rising from 14% in 2015/16 to 22.2% in 2022/23 and stunting from 38% to 39%, consistent with a 2025 Global Hunger Index score of 24.4, classified as serious (Global Hunger Index 2025), and with projections that up to 15 million people would face high levels of acute food insecurity in 2025 (FSIN and Global Network Against Food Crises 2025). Climate performance is qualified from within: although 80% of SDG 13 indicators are rated achieved, total greenhouse gas emissions rose from 181.11 to 209.07 Mt CO_2-equivalent between 2015/16 and 2023/24 and are classified as needing targeted intervention (Ministry of Planning and Development 2025).

National aggregates should nonetheless be read with care at basin scale. Under its inland-water interpretation of SDG 14, the Review reports national fish production rising from 48.36 to 138.13 thousand metric tons between 2015/16 and 2023/24 and the area of water bodies under formal protection increasing from 23.93 to 39.87 million hectares, while fishery value added remained at 0.1% of gross domestic product; under SDG 15, forest cover rose from 15.5% to 23.6% while the Red List Index remained unchanged at 0.85 (Ministry of Planning and Development 2025). Aggregate gains of this kind, driven substantially by aquaculture and by input support to fishery villages, are not evidence that conditions have improved in any particular basin, and are not inconsistent with the projected losses in Lake Turkana fisheries productivity discussed in Section 1.6. Conditions in the lower Omo therefore contribute to the national position but are neither the sole nor the primary driver: national food insecurity is attributed principally to drought, flooding, conflict and macroeconomic shocks concentrated in Amhara, Oromia, Tigray and the southern and southeastern pastoral areas (FSIN and Global Network Against Food Crises 2025), and national policy presents continued irrigation development as part of the response. Against this backdrop, this review synthesizes the available evidence on how flow regulation, irrigation abstraction and climate change are altering the ecological functions of the lower Omo, its floodplain and the Omo delta, and links the evidence with associated ecosystem service and SDG trade-offs.

1.1 The Omo-Gibe River Basin

Covering an area of approximately 79,000 km^2 within Ethiopia (149,000 km^2 when Lake Turkana's additional watersheds are included, principally the Turkwel and Kerio catchments, which lie in Kenya), and ranking third among Ethiopia's basins by water potential, the Omo-Gibe Basin is located in south-western Ethiopia (Figure 1; Dondeyne et al. 2024; Worku et al. 2014). The basin extends approximately 550 km in length, spans elevations from 719 to 3,086 m above mean sea level (m a.m.s.l), and generates around 16.6 BCM of runoff annually, equivalent to 14% of Ethiopia's annual surface water resource (Anose et al. 2022). Within Ethiopia, the basin lies within four regional

states: Oromia, South Ethiopia, Central Ethiopia, and Southwestern Ethiopia People regional states, encompassing 83 woredas and 2,385 kebeles, and is home to approximately 14.6 million people, the majority of whom depend on agriculture and fisheries (Water and Land Resource Centre 2024a; Meshesha Yericho and Mulugeta 2019). The Gibe River's headwaters lie on the slopes of Mt. Gurage in Ethiopia's central highlands at elevations exceeding 2,500 m a.m.s.l. Following its confluence with the Gojeb River, the basin's largest tributary, the river is thereafter known as the Omo River. Within its upper and middle reaches, the Omo River flows through steep valleys characterized by deep gorges before descending into extensive lowland plains and ultimately discharging through a delta into Lake Turkana (Chaemiso et al. 2016; Dondeyne et al. 2024). Lake Turkana is a large saline lake straddling the border between Southern Ethiopia and the hyper-arid lands of northern Kenya (Kolding 1992).

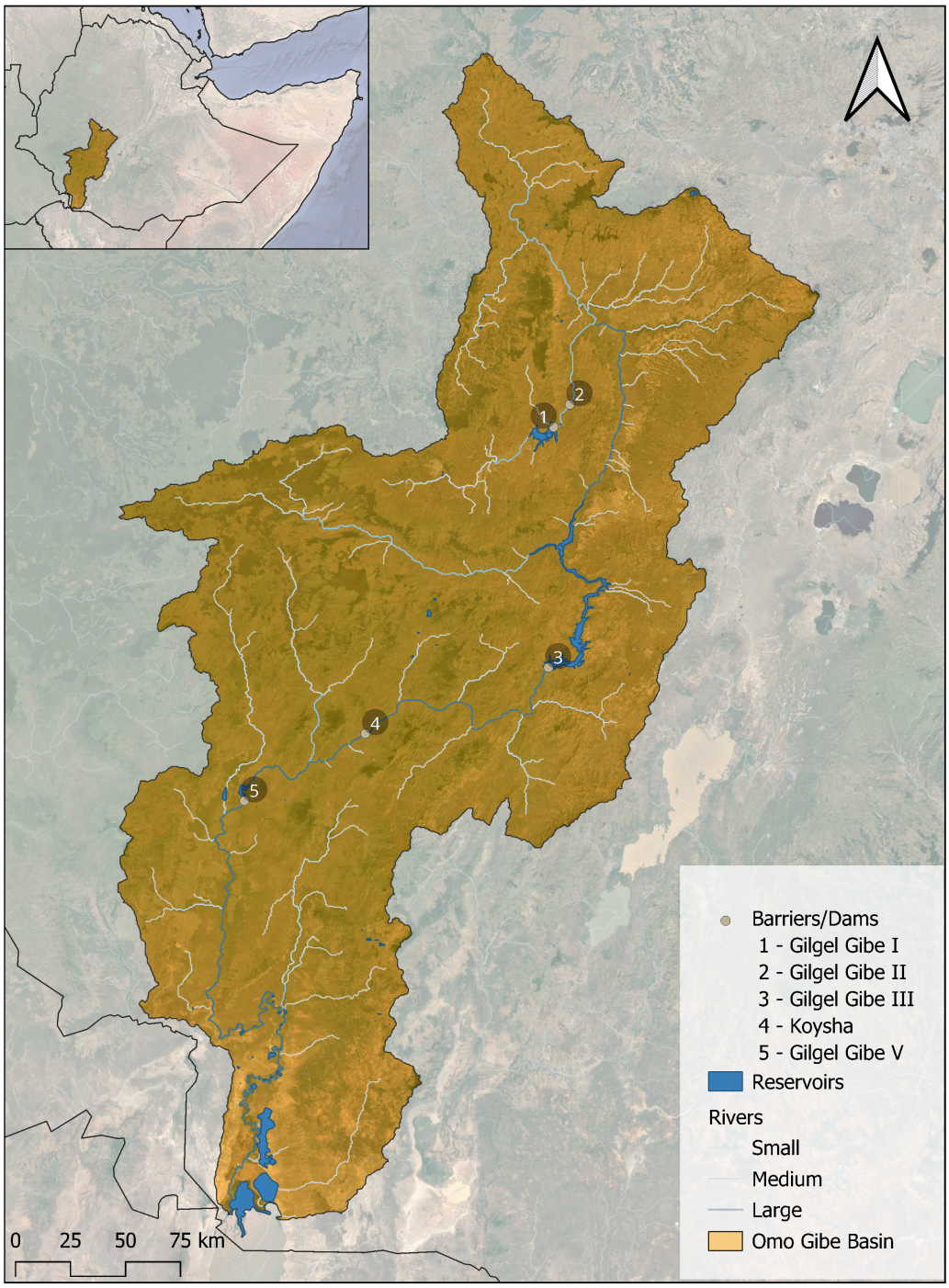

Figure 1. Major reservoirs and dams of the Omo-Gibe basin, Ethiopia. Koysha/Gibe IV (4) is still under construction and not yet operational, and Gibe V (5) has not yet proceeded to construction.
Source: Authors

The Omo-Gibe River Basin has a pronounced climatic gradient: the river originates in humid highlands and flows through increasingly arid lowlands, culminating in hyper arid conditions at its deltaic terminus in Lake Turkana (Dondeyne et al. 2024). Mean annual rainfall declines from 1,900–1,950 mm in the central and northern highlands to 300–450 mm in the south, while mean annual temperature rises from 17–24°C in the highlands to approximately 30°C in the southern lowlands. Precipitation is unimodal in the north and center of the basin and bimodal in the south (Bayana et al. 2024; Chaemiso et al. 2016; Lukas et al. 2025). Table 1 summarizes the basin's most prominent agroecological zones.

Only 28% of precipitation in the upper basin contributes to surface runoff, while a further 13% contributes to groundwater recharge; the remaining 59% is lost through evapotranspiration (Begashaw et al. 2024). Consequently, upstream changes, including land-use change and moderate reductions in precipitation, may cascade through the system and contribute to water deficits in the lower basin.

Farming in the basin is constrained by topographic and soil limitations. In the basin's moist highland reaches, the Gibe and Omo rivers flow through deep gorges at 700 m above sea level, while arable land is largely restricted to plateaus at 1,200 m above sea level. In the lowlands, impermeable Planosol soils constrain drainage (Elias et al. 2025; Meshesha Yericho and Mulugeta 2019) and restrict crop root penetration. Consequently, pastoralism constitutes the dominant agricultural land use across the basin (44%), followed by mixed farming (23%) and forestry (15%), with a diverse range of minor land uses comprising the remainder (Water and Land Resource Centre 2024a). Coffee is the most commonly grown cash crop in the humid highland regional states of the upper and middle basin, notably South West Ethiopia Peoples' Region (South West Ethiopia Peoples' Region Finance and Economic Development Bureau 2022). Effluent from coffee processing and associated agricultural runoff have been linked to distinctive BOD_5 traces and elevated conductivity in the basin's rivers (Awoke et al. 2016).

The lack of a natural growing season near the river's deltaic terminus, due to aridity, renders lower-basin agriculture unviable without conveyed water, which was traditionally provided through flood recession (Dondeyne et al. 2024; Hodbod et al. 2019). Cultivation is intensifying across most northern catchments, while flatter, poorly drained bottomlands support eucalyptus plantations and dry-season grazing; the eastern basin is densely settled and intensively farmed, and the south is undergoing rapid deforestation (Bayana et al. 2024; Orkodjo et al. 2022).

The lower Omo terminates in a delta at 360 m a.m.s.l., which forms the downstream limit of the reach considered in this review (Studio Pietrangeli 2016; Water and Land Resource Centre 2024b; Ethiopian Electric Power 2016a). The Omo River is the dominant source of inflow to the Lake Turkana, contributing more than 80% of its freshwater supply, and the lake is therefore retained here as the receiving body for flows leaving the floodplain and delta. Its sensitivity to that inflow is long established: the lake loses on average 8.3 mm of water daily, reflecting its location in a hyper-arid region (Avery and Tebbs 2018), and with an average saline concentration of 2,500 ppm and alkalinity of pH 9.2 it was historically considered the most saline water body in East Africa that supports a normal fish fauna, maintained and buffered by freshwater inflows over smectite clays (Yuretich and Cerling 1983).

Table 1. Most prominent agro-ecological zones of the Omo-Gibe River Basin.
Source: Water and Land Resource Centre (2024b)

Zone	Basin area (%)	Elevation (m a.s.l)	Mean annual rainfall (mm)
Wet Woyna Dega	26	1,500-2,300	>1,400
Moist Woyna Dega	18	900-1,400	900-1,400
Dry/Moist Kolla	36	<500	<500

1.2 Historical Flood-Pulse Regime

A staggered flood pulse traditionally characterized this endorheic basin's hydraulic regime: the upper basin experienced highland rains between April and September, which induced lower floodplain flooding between July and October, while Lake Turkana's maximum water level occurred between October and December (Kolding 1989). The pulse was protracted rather than flashy, with the seasonal rise lasting three to four months before receding.

The pulse drove biological and geomorphological processes throughout the basin. Its rising limb delivered breeding and migratory cues to fish and other aquatic biota; overbank flow redistributed sediment and nutrients across levees and floodplains, maintaining soil fertility and ecological succession in riparian woodlands; and inundation recharged the alluvial aquifers of the lower river. The receding limb exposed moist, freshly deposited soils that sustained flood-

recession cultivation across the lower basin, which supplied a substantial share of the annual dietary intake of Lower Omo agropastoral communities (Carr 1998; Hodbod et al. 2019).

At the basin terminus, the pulse was expressed as high annual variation in Lake Turkana's water level (Butzer 1971). Prior to the commissioning of Gibe III, the lake experienced intra-annual level oscillations averaging 1.0–1.5 m, which exceeds those of almost every other natural lake worldwide (Avery and Tebbs 2018; Bloszies and Forman 2015; Butzer 1971; Kolding 1992). It is the amplitude of these oscillations, rather than the absolute volume of inflow, that governed the extent of the lake's productive littoral zone.

1.3 The Gibe Hydropower Cascade and Kuraz Sugar Development Project

The Omo-Gibe River Basin is undergoing large anthropogenic transformation, driven by the hydropower cascade (Gibe I-III, with Koysha/Gibe IV under construction) in its middle reaches, and the Kuraz Sugar Development Project (KSDP) in its lower reaches. These flow regulations and abstractions are transforming the river's hydraulic flow regime towards an engineered flow regime aligned with electricity demand and irrigation schedules, with the resulting impacts extending downstream to the Lower Omo Valley and Lake Turkana. Irrigation is by far the largest consumptive water use in the basin, accounting for nearly 92% of the 5,443 Mm^3 baseline total demand estimated of all sectors for 2017 (Orkodjo et al. 2022).

The Gibe hydropower cascade consists of three operational projects—Gilgel Gibe I, II, and III—and a fourth project, Koysha (Gibe IV), which is under construction. Table 2 summarizes the key characteristics of the four projects.

Table 2. Characteristics of the Gibe hydropower cascade.

Parameter	Gibe I	Gibe II	Gibe III	Koysha/ Gibe IV
Location	Gilgel Gibe tributary, ~7.83°N, 37.32°E	Damless plant; 26 km diversion tunnel from intake at 7.75°N, 37.56°E	Main Omo-Gibe River, ~6.84°N, 37.30°E (max level 892 m asl)	~6.58°N, 36.57°E
River	Gilgel Gibe River (tributary of the Omo River)	Inflow at Gilgel Gibe River; outflow at Omo River	Omo River	Omo River
Installed/ To be Installed	184 MW	420 MW	1,870 MW	2,160 MW
Reservoir Capacity	0.92 BCM	No reservoir	14.7 BCM	6 BCM
Annual Throughput	No explicit value (power intakes designed for 102 m3 s-1)	78.4 m3 s-1	438.2 m3 s-1	540 m3 s-1
Exploitable Net Head (max/avg)	232.3 m / 207.3 m	505 m / 470 m	211 m / 186 m	158 m / 150 m
Status	Commissioned 2004	Commissioned 2010	Commissioned 2016	Under construction, originally scheduled for commissioning in 2025 (~65-70% complete as of October 2025)
References	Ethiopian Electric Light and Power Authority (1997)	(Colombo & Maran, 2004)	(Ethiopian Electric Power Corporation 2009b; SOGREAH Consultants, 2010)	(Ethiopian Electric Power 2016b)

For the commissioned Gibe I–III projects, Yesuf (2012) estimated consumptive water losses of 2.3% and modelled Gibe III as reducing wet-season flood peaks by approximately 36% while increasing dry-season flows by 135%. These estimates indicate the modelled direction and approximate magnitude of flow redistribution but should be distinguished from direct post-commissioning measurements of downstream ecological or livelihood change. They derive from simulation rather than from gauged post-commissioning discharge and observed flow data could not be substituted here because of the hydrometric deficits described in Section 1.8.2. Within this combined estimate, Gibe I's smaller reservoir (0.92 BCM) provides some incremental flow regulation, while Gibe II operates as a diversion-only, non-regulating run-of-river scheme; Gibe III's much larger reservoir (14.7 BCM)

therefore accounts for the great majority of the cascade's regulating effect. Following Gibe III's commissioning, the lower Omo's seasonal flood pulse was substantially regulated, reducing the reliability of the flood-recession processes on which local agropastoral livelihoods had depended (Kamski 2016; Hodbod et al. 2019). No study comparing the reliability of flood-recession agriculture with and without the dams was identified, and no quantitative flood-frequency analysis comparing pre- and post-regulation flood risk for this reach was found; reported disruption should therefore be read as documented local perception rather than as a measured change in reliability or in flood exposure. Field-based research by Gebeyehu and Abbink (2022) documents local perceptions of livelihood disruption, land-use pressure and food-security effects associated with the Omo-Kuraz sugar projects, while Hodbod et al. (2021) provides a broader social-ecological synthesis that interprets these changes as contributing to declining resilience and reduced adaptive capacity among affected lower Omo communities. More recent remote-sensing analysis by Desta et al. (2024) indicates that the Omo-Gibe Basin contains substantial areas biophysically suitable for flood-based farming, although this finding does not establish how much of that potential remains accessible under regulated post-Gibe III flow conditions.

Announced in January 2011, the Kuraz Sugar Development Project (KSDP) forms part of a broader state-led development strategy centered on Ethiopia's transition towards middle-income status. Yitbarek and Kamski (2023) characterize the project as also serving to extend central state authority into peripheral regions, and record that it has been presented in official communications as a means of transforming areas previously described as unproductive and conflict-affected into centers of socio-economic development. The project was initially envisaged to encompass 175,000 ha of floodplains downstream of Koysha/Gibe IV, but the shelving of the planned Gibe V scheme, which has not proceeded to construction, subsequently led the government to reduce the planned irrigated area to 100,000 ha. At full development of 100,000 ha, the scheme is expected to abstract approximately 1.1-1.9 km³ of water per year, representing between 4-12% of Gibe III's total annual discharge; this is a design-based modelled estimate rather than a measured abstraction, and actual as distinct from designed abstraction remains unquantified (Section 1.8.3). Its long-term viability is consequently closely linked to the reliable availability of regulated water supplied by Gibe III and by the Koysha/Gibe IV project, which is still under construction and not yet operational (Yitbarek & Kamski, 2023; Dondeyne et al. 2024).

Implementation of the KSDP may have progressed more slowly than originally designed, though verified progress data are limited. Conveyance losses of 30-50% deliver only 20-25% of required water to fields, producing actual yields of 45 t/ha against a 100 t/ha projection (Eshetu et al. 2021); the Ethiopian Sugar Corporation has accumulated at least US$3.6 billion in loans between 2011 and mid-2016 (Kamski, 2016); and the accompanying villagization scheme for pastoralist communities has failed to deliver promised irrigation, out-grower schemes, or basic services, leading many households to abandon settlement sites (Gebresenbet, 2021; Gebeyehu & Abbink, 2022; Yitbarek & Kamski, 2023). Wage labor on the sugar estates is documented as an employment opportunity for some households, though its scale has not been quantified in the sources reviewed (Gebresenbet 2021; Gebeyehu and Abbink 2022).

1.4 The Gibe Cascade in Ethiopia's Energy Context

Ethiopia's electricity system is overwhelmingly renewable, with hydropower supplying approximately 95% of generation, yet only around half of the population has access to any form of electricity and over 90% of primary energy remains tied to traditional biomass (Ministry of Water and Energy et al. The National Electrification Program (NEP 2.0) targets 65% grid-connected and 35% off-grid coverage nationally by 2025, requiring approximately 8.2 million new grid connections, though progress data specific to the Omo-Gibe basin's woredas (districts) were not identified (Ministry of Water and Energy/Danish Energy Agency 2024). 2025; Weldengus and Berhe 2026; Yalew 2022). Amid a national ambition to reach middle-income status through structural transformation leveraging high gross domestic product growth rates, which averaged 8–10% between 2010 and 2020, electricity demand is projected to grow by 9.5–14.4% annually through 2030. Expanding reliable generation has therefore been identified as a necessary precondition for industrialization and foreign-exchange stability (Mamo 2024; Weldengus and Berhe 2026; Yalew 2022). Within this framing, the Gibe cascade—2,474 MW installed across Gibe I–III, with Koysha/Gibe IV projected to add 1,800 MW—is treated as the principal supply-side response, allowing projected regional electricity exports to reach 35,303 GWh/year by 2037 and yielding 2.9 times as much hard-currency revenue for each additional dollar of cost (Lavers et al. 2021; Ministry of Water and Energy and Ethiopian Electric Power 2022; Ministry of Water and Energy et al. 2025). In short, the Gibe hydropower cascade is intended to support industrial parks, electrified transport, and Ethiopia's position as a regional power hub while maintaining net-zero compatibility (Ministry of Water and Energy et al. 2025; Weldengus and Berhe 2026).

However, this energy-industry narrative is complicated by structural constraints. Design revisions increased Gibe III's installed capacity from 1,200 MW to 1,870 MW while average energy generation remained at 6,500 GWh, because average generation is set by inflow and reservoir storage rather than by turbine capacity, so the additional capacity raises peak output rather than firm annual energy; the plant load factor consequently fell from 62% to 40%, and Koysha exhibits an analogous decline, from 50% to 34%, indicating that headline installed-capacity figures overstate actual deliverable energy (Lavers et al. 2021). When Gibe III was commissioned in

2016, insufficient substations could not transmit its output; and thus, transmission and distribution losses may have reached 26%. Similarly, pressure to operate the dam at high output had by May 2019 depleted reservoir storage so severely, that severe rationing was required (Lavers et al. 2021). Ethiopian businesses experience approximately 39 power interruptions per month, and the country's reliance on hydroelectric power has been described as insufficient for industrial energy demands during dry seasons, when a typical dry year is modelled to lack 10 TWh of hydro generation (Ministry of Water and Energy et al. 2025; Manufacturing Industry Potential of South Ethiopia Regional State, 2024; Ministry of Water and Energy and Ethiopian Electric Power 2022). Approximately 25% of installed capacity is currently inactive owing to hard-currency shortages, while hydropower production is projected to decline by 2065 under climate change (Mekonnen et al. 2022). At national scale, hydropower expansion may interact with agricultural expansion through competing demands for water and land, although within the Omo-Gibe system the principal irrigation schemes lie downstream of the cascade and depend on regulated releases rather than competing directly with upstream hydropower infrastructure. Taken together, these factors suggest that the cascade's contribution to industrialization is bounded by hydrological, infrastructural, and financial constraints (Ministry of Water and Energy et al. 2025; Girgibo et al. 2025; Yalew, 2022). These figures should be interpreted cautiously for three reasons: first, peer-reviewed evidence on actual energy generation from Gibe III remains limited; second, the reviewed studies do not appear to use a continuous historical generation time series for Gibe III, whether monthly or annual, since commissioning in 2016, relying instead on design documents, simulated discharges, or inferred generation; and third, recent studies are insufficient to characterize the current performance of the cascade under present operating, climatic, and grid conditions. Inflows have also been comparatively high in recent years, so generation performance may have improved relative to these earlier estimates, although no published generation record is available to confirm this.

1.5 Ecological Functions and Ecosystem Services

The ecological functions of the lower Omo and its floodplain sit at the intersection of competing SDG trajectories, making them a useful lens through which infrastructure-driven development trade-offs against ecological functioning can be measured. The flood-pulse regime described in Section 1.2 sustained overbank inundation, alluvial recharge, riparian succession and flood-recession cultivation across the lower basin, and at the terminus sustained a productive Aquatic-Terrestrial Transition Zone that ranged from 42.5 to 157.5 km² (Gownaris et al. 2017).

Nitrogen availability has historically limited primary productivity in Lake Turkana, as evidenced by algal bioassays and direct measurements from the lake's central regions between 1987 and 1988, which reported a mean total nitrogen concentration of 1.1 mg L^{-1} (Liti et al. 1991). Consequently, nutrient inputs delivered by the Omo River's seasonal flood pulse remain an important control on phytoplankton dynamics and chlorophyll-a levels, which underpins SDG 14 (life below water) (Tebbs et al. 2020). Modelling by Tebbs et al. (2020), using a weighted least-squares regression between lake-wide chlorophyll-a concentrations and Omo River inflow, projected a decline in chlorophyll-a following the filling and subsequent regulation of Gibe III. Applying the regulated-flow hydrograph reported by Avery and Tebbs (2018) to the same relationship suggests that the potential decline may be greater than the estimate originally reported by Tebbs et al. (2020), although this should be treated as a derived projection rather than an independently observed post-regulation trend. This interpretation also requires caution because Gibe III regulation is not the sole driver of Lake Turkana's level dynamics: recent lake expansion, flood exposure and shoreline recession reflect interacting influences including rainfall variability, evaporation, land-use change, and possible groundwater or tectonic controls, with Byrne et al. (2024) attributing rising lake levels across central East Africa during 2000–2023 primarily to increasing rainfall and land-use intensification. Thus, changes in Lake Turkana's flood pulses and recession zones should not be attributed to dam regulation alone, even though regulation of the Omo inflow remains ecologically important. Within the lower Omo-Gibe floodplain and riverine system, the 2010 European Investment Bank review anticipated that reduced turbidity under regulated flow could promote plankton and algae growth, increasing food availability for fish fry. This potential local increase in planktonic activity should not, however, be interpreted as an unqualified ecological benefit, because project documentation also identifies a risk of eutrophic conditions developing in the Koysha reservoir (SOGREAH Consultants 2010; Ethiopian Electric Power 2016a).

Table 3 below summarizes the lower basin's provisioning, regulating, cultural, and supporting services, and their correspondence to specific SDGs.

Table 3. Ecosystem services of the lower Omo-Gibe Basin and their alignment with the SDGs.

Service category	Function	Beneficiaries / Evidence	Linked SDG
Provisioning	Flood-recession agriculture, dry-season grazing, riverine fisheries and access to floodplain resources supported by seasonal inundation, recession processes and Omo River flow; these services are affected by dam regulation, irrigation development and lower-basin hydrological variability. (see also Table 5 on reservoir-fisheries production as a partial offset).	Lower Omo-Gibe agropastoral, pastoral and riverine communities, particularly households dependent on flood-recession cultivation and floodplain grazing. Available estimates suggest that approximately 67,600–90,000 people relied on flood-recession agriculture in the lower Omo. Evidence combines estimates of flood-recession dependence, field-based livelihood accounts and broader resilience synthesis (SOGREAH Consultants 2010; Hodbod et al. 2019; Gebeyehu and Abbink 2022; Hodbod et al. 2021).	SDG 1 (No Poverty); SDG 2 (Zero Hunger); SDG 15 (Life on Land)
Regulating	Seasonal flood pulse distributes sediment and nutrients, sustains floodplain fertility, supports riparian succession, maintains wetting-drying dynamics across floodplain wetlands, and contributes to alluvial recharge in the lower Omo-Gibe system. Flood-risk regulation is also relevant here: regulation has attenuated the extreme flood peaks that historically caused loss of life and asset damage, but this function has shifted rather than simply improved, since sudden or excessive releases have themselves caused downstream flooding (OCHA/IOM/VSF-G 2024).	Lower Omo floodplains, riparian woodlands, seasonal wetlands, alluvial aquifers and Omo delta communities; evidence includes flood-pulse ecology, lower-basin livelihood accounts and hydrological assessments focused on sediment, recharge and floodplain function (Carr 1998; Endaylalu and Arsano 2024; Gebeyehu and Abbink 2022; Dondeyne et al. 2024).	SDG 6 (Clean Water); SDG 15 (Life on Land)
Supporting	Aquatic biodiversity, riparian forests, floodplain wetlands, riverine habitats and flood-dependent biota supported by Omo River flow, nutrient delivery, floodplain inundation, wetting-drying dynamics and basin-scale habitat connectivity.	Lower Omo-Gibe riverine, floodplain and riparian ecosystems; evidence includes fish diversity summaries, riparian and wetland ecology, and lower-basin floodplain-function accounts (Wakjira and Getahun 2017; Ojwang et al. 2016; Carr 1998; Endaylalu and Arsano 2024).	SDG 14; SDG 15
Cultural	Seasonal flooding and recession structure agricultural, pastoral, mobility and cultural calendars; access to	Lower Omo-Gibe agropastoral and pastoral communities, including groups whose livelihoods are organized around	SDG 2 (Zero Hunger)

Service category	Function	Beneficiaries / Evidence	Linked SDG
	floodplain cultivation, grazing areas, riverine resources and settlement patterns is shaped by the timing, duration and reliability of lower Omo inundation.	seasonal flood-recession cultivation, grazing, mobility and river access; evidence includes lower-basin cultural-ecological and livelihood accounts, while impacts vary by location and evidence type (Endaylalu and Arsano 2024; Gebeyehu and Abbink 2022; Hodbod et al. 2019).	

1.6 Impact Pathways and Empirical Evidence

Since the early 2000s, the Gibe cascade and the KSDP (revised target 100,000 ha) have been converting a flood-pulse-driven flow regime into an engineered regime. This review uses six causal pathways (P1-P6), summarized in Table 4, as an analytical framework for linking these interventions to the lower Omo, its floodplain and the delta. Their derivation from the evidence base is described in Section 2.8.

Table 4. The six causal impact pathways (P1-P6) linking Gibe cascade and KSDP interventions to the lower Omo, its floodplain and the delta, and thence to Lake Turkana.

Pathway	Mechanism	Consequence
P1 Dam regulation & flow alteration	Dam regulation redistributes Omo flows by reducing wet-season peaks and increasing dry-season releases; the scale of downstream ecological response remains partly modelled and should be distinguished from observed post-commissioning changes. Climate variability may compound or offset these effects.	Reduced reliability of seasonal flood-pulse cues and flood-recession processes; implications for biological cueing are inferred from flood-pulse ecology and flow-regulation evidence rather than directly measured for lower Omo-Gibe biota (Yesuf 2012; Kamski 2016; Hodbod et al. 2019; Lukas et al. 2025).
P2 Irrigation abstraction & inflow reduction	Water abstracted for lower Omo irrigation reduces return of regulated flows to the delta and lake; the magnitude depends on realized irrigated area, conveyance losses, irrigation efficiency and return flows.	Livelihood risks arise through reduced flood-recession reliability and irrigation-related land-use change; field-based evidence documents local perceptions of disruption and food-security effects, while resilience impacts are partly synthesized or inferred (Gebeyehu and Abbink 2022; Hodbod et al. 2021).
P3 Sediment trapping & nutrient retention	Reservoirs may intercept sediment and nutrients, reduce downstream sediment delivery and altering nutrient inputs to floodplains, the delta and Lake Turkana; the ecological consequences depend on flow regulation, catchment erosion, land-use change and lake-level dynamics.	Potential reduction in floodplain fertility, delta sediment supply and nutrient-driven productivity; attribution of delta or shoreline change should be made cautiously because recent lake expansion reflects multiple drivers (Dondeyne et al. 2024; Byrne et al. 2024).
P4 Groundwater recharge loss	Reduced overbank inundation may weaken alluvial aquifer recharge, but groundwater exchange around the lower Omo remains poorly quantified. This recharge pathway is distinct from groundwater's role in sustaining dry-season baseflow; regulated flow has substantially increased dry-	Possible contraction of the subsurface buffer; confidence is limited by sparse lower-basin groundwater monitoring and uncertain lake-groundwater exchange (Begashaw et al. 2024; 2025).

Pathway	Mechanism	Consequence
	season baseflow (from a natural 150-200 m³/s to approximately 490-525 m³/s), which may reduce reliance on groundwater for baseflow support even as reduced overbank flooding continues to constrain aquifer recharge.	
P5 Turkana Jet evaporative amplification	Persistent low-level easterly winds through the Turkana channel contribute to regional aridity and strong evaporative demand; evaporation interacts with rainfall variability and land-use change in shaping lake-level change. This pathway is a climatic control that operates independently of the Gibe cascade: it modulates the basin water balance rather than being driven by dam operation, although open water added by the reservoirs may have a local, and as yet unstudied, influence on atmospheric moisture fluxes.	May amplify freshwater deficits during dry periods, although recent lake expansion indicates that rainfall and land-use effects can dominate over evaporative losses at regional scale (Nicholson 2016; Byrne et al. 2024).
P6 Land-cover & climate feedback	Upper-catchment land-cover change, rainfall variability and warming alter runoff, sediment yield, evapotranspiration and regional lake expansion; these drivers interact with, rather than simply follow from, dam regulation.	Changes in runoff, erosion, evapotranspiration and lake extent can modify ecological pathways independently of the hydropower cascade; recent regional evidence attributes lake-level rise primarily to rainfall and land-use intensification (Hirbo Gelebo et al. 2022; Byrne et al. 2024).

These pathways interact, and in several cases compound one another, but their effects should not be interpreted as a single linear chain attributable only to dam regulation. Flow regulation can reduce the reliability of seasonal flood-pulse cues, while irrigation abstraction, sediment and nutrient retention, groundwater recharge loss, evaporative demand, rainfall variability and land-use change interact to shape downstream ecological conditions. Some of these interactions are offsetting rather than additive: a shorter inundation period reduces floodplain evaporation and infiltration losses and may therefore increase the volume delivered to the delta and the lake, partly compensating for irrigation abstraction, while at the same time reducing alluvial recharge, flood-recession cultivation and dry-season grazing. The net effect on floodplain services therefore has to be assessed jointly rather than pathway by pathway. Environmental flow provisions likewise need to be assessed against multiple functions of the historical flood pulse. The Gibe III ESMP's proposed 10-day artificial flood cannot replicate the three-to-four-month inundation required for floodplain recharge, and even this limited measure has not been consistently implemented; Tebbs et al. (2020) estimated that a 30-day flood could restore approximately 60% of pre-dam chlorophyll-a, compared with approximately 20% under the current 10-day provision. These values should be treated as modelled ecological responses rather than observed post-regulation outcomes.

Table 5. Empirical and modelled evidence of hydrological and ecological impacts at Lake Turkana, the receiving boundary downstream of the Omo delta, compared with SOGREAH Consultants (2010) claims and recent evidence since 2021.

Indicator	Value	Context / Source	Claims as per SOGREAH Consultants (2010)	Recent evidence (2021–present)
Lake-level drop during reservoir filling	1.5 m	2015–2016 (Avery and Tebbs 2018; Human Rights Watch 2017)	Predicted a ~1.7–1.8 m drop from first impoundment, close to the lake's annual natural fluctuation (~1.5 m) and within historical inter-annual range. ESIR characterized NGO claims of 10–12 m drops as "not supported by any scientific evidence".	Recent lake-expansion evidence qualifies earlier decline projections: Byrne et al. (2024) report rising lake levels across central East Africa during 2000–2023, primarily associated with rainfall and land-use intensification.
Ferguson's Gulf recession	up to 1.7 km	During filling (Avery and Tebbs 2018)	—	Recent evidence of lake expansion means shoreline recession should be interpreted as period-specific rather than a continuing trajectory; attribution requires separating dam filling, rainfall, temperature rise, land-use change and lake hydrodynamics (Byrne et al. 2024; Water, Peace and Security 2024).
Chlorophyll-a decline during filling	~30%	Tebbs et al. 2020	—	No post-2021 empirical chlorophyll-a monitoring study for the post-Gibe III operational period is identified in the review; the value remains a modelled or remotely sensed inference from earlier work.
Chlorophyll-a projected decline	19–44%	Under irrigation scenarios (Tebbs et al. 2020)	—	Lake-level change is now understood as multi-driver, with rainfall and land-use intensification important regional controls (Byrne et al. 2024). The underlying relationship is calibrated on inflow volume alone and does not represent nutrient loading from irrigation return flows, which would act in the opposite direction; the projected decline should therefore be read as a flow-driven estimate rather than a full nutrient balance. No source in the evidence base quantifies agrochemical or fertilizer runoff from irrigated agriculture for the Omo-Gibe basin specifically, but such

Indicator	Value	Context / Source	Claims as per SOGREAH Consultants (2010)	Recent evidence (2021–present)
				runoff would be expected to increase, not decrease, downstream nutrient loads, partially counteracting the sediment/nutrient-retention effects described elsewhere in this review.
Inflow controlled under full regulation	~80% (modelled, not observed)	Full cascade estimate (Gownaris et al. 2017)	States that Gibe III alone controls about 50% of the Omo catchment area and about 70% of total runoff. The ~80% figure applies to the full cascade including Gibe IV, not Gibe III alone.	Recent work supports a more cautious framing: regulation is an important control on Omo inflow, but lake-level outcomes also depend on rainfall variability, land-use change, evaporation and lake hydrodynamics (Byrne et al. 2024; Water, Peace and Security 2024).
Lake-level oscillation compression	1.0–1.5 m → ~0.3 m	Full regulation projection (Gownaris et al. 2017; Ethiopian Electric Power 2016a)	—	Recent lake expansion means this compression estimate should be treated as conditional on earlier lake-state assumptions; present amplitude and exposed-zone dynamics require updated monitoring (Byrne et al. 2024).
ATTZ contraction	75%	Full regulation projection (Gownaris et al. 2017)	The review noted that delta size fluctuates strongly even under natural conditions and expected future variation to remain within the observed historical range.	Recent literature does not provide an updated empirical ATTZ estimate for the expanded lake state; the 75% value should therefore be treated as an unvalidated projection requiring recalculation under present shoreline conditions (Byrne et al. 2024).
Fisheries yield decline	up to two-thirds (modelled, not observed)	Full regulation projection (Gownaris et al. 2017)	ESIR anticipated river fisheries would improve from increased dry-season flow (500 m^3/s), favoring year-round fishing along the river. It did not model Lake Turkana lake-fisheries yields.	Recent evidence points to livelihood pressure and fishing competition around the lower Omo. Reservoir fisheries in Gibe III, and prospectively in Koysha, may provide a partial offset in production terms.

1.7 Human-Ecological and Governance Dynamics

Field-based research in the lower Omo reports chronic food insecurity among approximately 95% of Nyangatom agropastoral households and links this to livelihood disruption, land-use pressure and the implementation of the Omo-Kuraz sugar projects (Gebeyehu and Abbink 2022). Broader social-ecological synthesis suggests that many lower Omo communities may now be operating at, or close to, the limits of adaptive capacity because large-scale development has replaced some of the flood-recession, grazing and river-access functions on which traditional strategies depended (Hodbod et al. 2021). Water, Peace and Security 2024 frame this as a form of hydrological insecurity, or "flooding paradox", in which localized water shortages below the reservoirs coexist with flooding further downstream, including in Dasanech areas. This pattern should not be attributed to reservoir operations alone: it reflects the interaction of seasonal variability, reservoir release schedules, uneven distribution of risks and benefits, intervening anthropogenic activities and lake hydrodynamics (Water, Peace and Security 2024). Nor are the social effects uniformly negative: regulation has also attenuated the extreme flood peaks that historically caused loss of life and damage to assets in the lower basin, and the associated development has generated employment and service infrastructure for some groups, so gains and losses fall on different populations rather than cancelling one another. This attenuation should not be overstated, however: a 2024 joint OCHA/IOM/VSF-G mission report documents flooding in Dasenech woreda in November 2023 and May 2024 attributed explicitly to excessive or sudden release of water from Gibe III combined with Omo River overflow, indicating that regulated releases have also caused recent downstream flooding (OCHA/IOM/VSF-G 2024). Altered flood and reservoir regimes may also carry public-health implications distinct from these food-security and ecological pathways: dam reservoirs across African river basins, including the Omo-Turkana system, have been identified as malaria transmission hotspots, with small dams contributing a disproportionate share of dam-attributable cases regionally (Kibret et al. 2021).

Governance gaps compound these risks. Although Ethiopian legislation requires the establishment of Basin Authorities under Proclamation No. 534/2007, with this institutional framework further reinforced by the requirement to establish Basin High Councils under Proclamation No. 1375/2025, the Omo-Gibe River Basin remains without a Basin Administration Office (BAO). The absence of such an office was identified by all survey respondents in Meshesha Yericho and Mulugeta (2019) as a key constraint to the implementation of Integrated Water Resources Management (IWRM) in the basin. This gap is associated with cascading governance challenges, including uncoordinated planning (89.1% of respondents), inadequate infrastructure and limited innovation (81.9%), and weak risk management (67.3%) (Meshesha Yericho and Mulugeta 2019). In addition to emphasizing the lack of a BAO, the BRIGHT project noted that the basin's hydrological boundaries do not coincide with administrative boundaries, contributing to fragmented management and sectoral disputes (Water and Land Resource Centre 2024b). Downstream effects also extend beyond Ethiopia through the Omo River's contribution to Lake Turkana, creating a need for coordinated assessment of flow regulation, irrigation abstraction, lake-level variability and ecological response. Scenario analysis indicates that cooperative management between Ethiopia and Kenya could generate substantially higher benefit-cost ratios than non-cooperative full-irrigation pathways (Englezos et al. 2023). However, earlier lake-depletion projections under non-cooperative trajectories should be interpreted cautiously in light of more recent evidence that Lake Turkana has expanded in extent and that lake-level change reflects multiple drivers, including rainfall variability, land-use change, evaporation and possible groundwater or tectonic influences (Byrne et al. 2024). The institutional evidence therefore points to a broader coordination deficit: the absence of a basin-level authority, limited cross-border data exchange, and top-down implementation of large-scale development have together constrained inclusive and adaptive governance for lower Omo-Gibe communities and downstream ecological systems (Meshesha Yericho and Mulugeta 2019; Water and Land Resource Centre 2024b; Englezos et al. 2023).

1.8 Knowledge Gaps

1.8.1 Substantive Hydrological and Ecological Gaps

First, groundwater exchange between the lake and surrounding regions remains unquantified, while declining terrestrial water storage (TWS) suggests the subsurface buffer may be contracting (Avery and Tebbs 2018; Yoshe 2024). Given the lake's recent expansion, a back-of-envelope water-balance calculation using bathymetric area-volume curves could in principle estimate recent annual inflow volumes, but the necessary bathymetric and evaporation data are not available in the evidence base reviewed here; this is flagged as a worthwhile follow-up calculation rather than a sourced figure. Because groundwater contributes an estimated 56% of river flow in the basin, the loss of overbank inundation from the flood pulse likely removes the dominant recharge pathway for alluvial aquifers, yet no monitoring of groundwater levels in the lower Omo Valley or around Lake Turkana currently exists. No post-2020 measurement of Lake Turkana's pH, alkalinity or salinity has been identified in the evidence base to test whether the observed lake expansion has diluted the historical 2,500 ppm TDS and pH 9.2 values reported by Yuretich and Cerling (1983); this represents an additional monitoring gap alongside groundwater exchange.

Second, while existing hydrological assessments in the basin evaluate surface water balance and crop water deficits (Hirbo Gelebo et al. 2022); the Turkana Jet, a persistent southeasterly low-level jet (LLJ) that flows through the Turkana Channel, existing throughout the year with peak intensity during boreal summer and autumn and playing a critical role in moisture transport and regional aridity (Hartman, 2018; Kinuthia & Asnani, 1982; Munday et al. 2021); has been largely absent from impact assessments. Because the jet maximizes wind-driven evaporation on 69-90% of days, its exclusion from basin water-balance models may lead to a systematic underestimation of both lake evaporative losses and regional irrigation requirements.

Third, the six impact pathways set out in Table 4 (P1-P6) have not been modelled as a coupled system. Because they reinforce one another, studying them in isolation prevents accurate quantification of compound ecological risks (Giuliani et al. 2022).

Fourth, environmental flow provisions do not reflect the full range of functions served by the flood pulse, and no framework links environmental flow requirements to measurable ecological outcomes. The current provision, identified in the Gibe III environmental and social management documentation, consists of a 10-day artificial flood and a continuous minimum flow of 25 m^3/s. This provision is ecologically insufficient for several flood-pulse functions: Tebbs et al. (2020) estimated that the 10-day flood would restore only approximately 20% of pre-dam chlorophyll-a concentrations in Lake Turkana, compared with approximately 60% under a 30-day flood. The stipulated minimum flow also lies far below the approximately 490–525 m^3/s dry-season flows currently observed under regulated operation, meaning that the floor is not currently a binding operational constraint, although it could become relevant in a severe drought scenario if releases approached that level. Chlorophyll-a is, however, only one of several relevant endpoints: inundation duration for floodplain recharge and recession cultivation, spawning and migration cues, sediment and nutrient delivery, and dry-season water quality would each require separate criteria. Indicative flow components derived from the evidence base for each of these functions are set out in Section 4.2 and are presented there as hypotheses for field validation rather than as prescriptive thresholds.

Fifth, there is a severe temporal gap in empirical ecological data. No empirical ecological monitoring studies, as distinct from model projections, were identified post-2017. Consequently, large projections of a 67-72% fisheries decline and a 75% contraction of the Aquatic-Terrestrial Transition Zone (ATTZ) remain empirically unvalidated in the post-Gibe III operational era.

1.8.2 Hydrometric Monitoring Deficit

Underlying these conceptual gaps, the hydrological monitoring network has deteriorated substantially. Haile et al. (2022) documented this deterioration directly in the Omo-Gibe basin, reporting that only 17% of 40 evaluated streamflow gauging stations were fully operational, with many records affected by short observation periods, missing data and inhomogeneity. The BRIGHT project's inception report subsequently states a requirement for 106 hydrometric stations in the Omo-Gibe basin, yet only 46 currently exist. This 57% deficit in the basin's hydrometric coverage, the largest deficit reported among all five BRIGHT basins, widens each year without intervention (Water and Land Resource Centre 2024b).

This severe lack of coverage means that 7 sub-basins (Alenga, Fato, Rebu, Denchiya, Waybe, Zigna, and Mansa) currently have absolutely no monitoring infrastructure (Fig. 2). Data availability and consistency are lacking, as most monitoring stations have abrupt data break points between 1997 and 2004. Recent discharge data (collected since 2005, and extending through 2015 to the present) has not been publicly available. This lack of homogeneous, usable data is primarily due to systemic failures to convert raw river stage readings into discharge data, coupled with unstable channel beds, infrequent maintenance, and outdated rating curves. Consequently, researchers are forced to rely on modelled data (Haile et al. 2022; Water and Land Resource Centre 2024b). One direct consequence is that a gauged pre- and post-commissioning hydrograph for the lower Omo, benchmarked against bank-full channel capacity, could not be constructed for this review; such a comparison would be the most direct means of establishing both the degree of regulation and the reduction in floodplain inundation, and should be a priority once accessible discharge records become available. However, indications within the limited available observational records suggest that modelled inflows and abstractions frequently diverge from actual basin conditions, masking the true severity of dry-season deficits and uncoordinated dam releases. However, indications within the Ministry of Water and Environment suggest substantial revitalization of the hydrometric monitoring network since 2025, which may allow for more rigorous quantitative studies in the future.

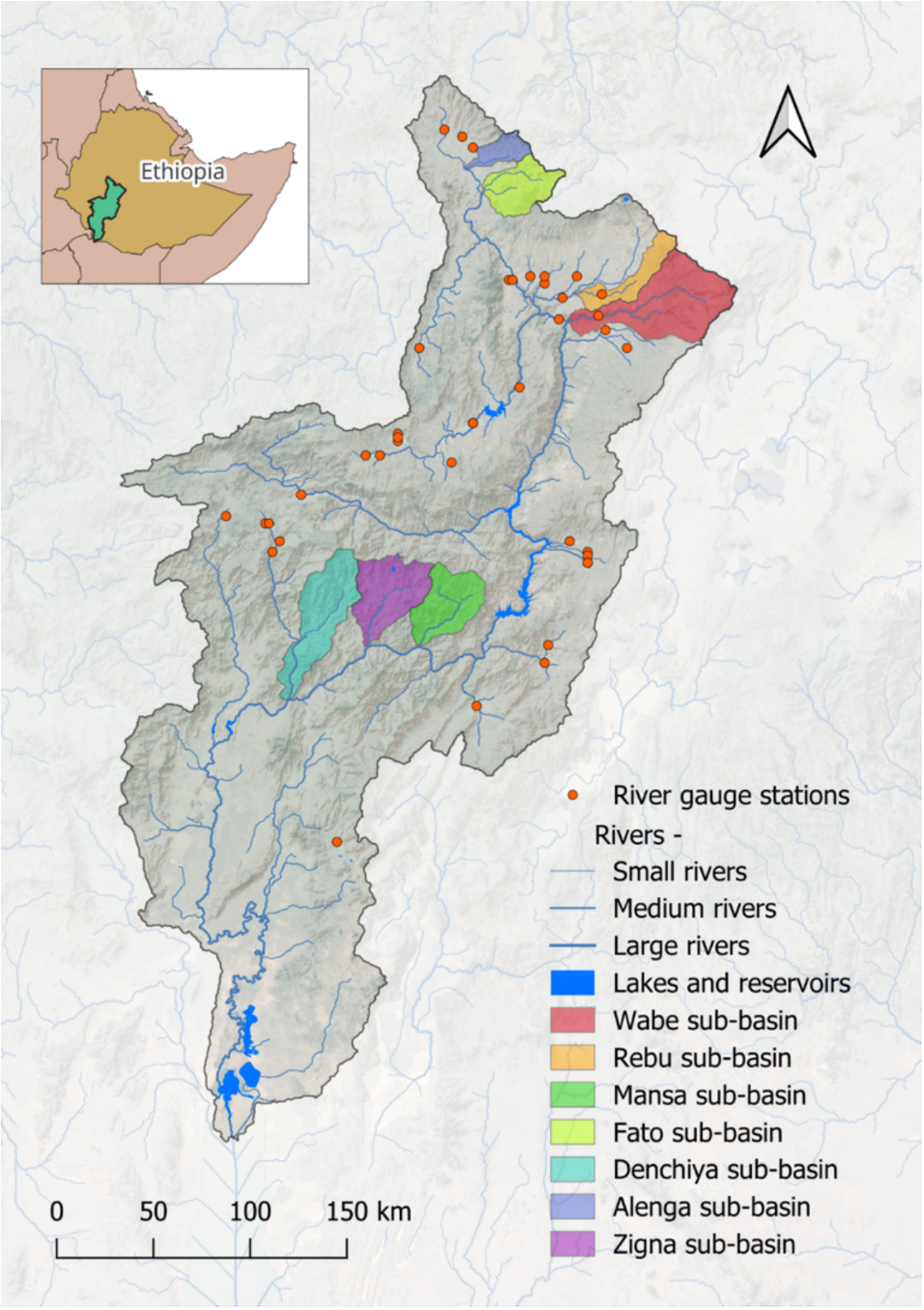

Figure 2. Map of the seven sub-basins (Alenga, Fato, Rebu, Denchiya, Waybe, Zigna, and Mansa) that currently have no monitoring infrastructure.
Source: Authors

1.8.3 Geographic and Methodological Gaps

Geographic research is heavily skewed toward the Kenyan side of Lake Turkana, while the Ethiopian side of the lake and the Omo Delta remain comparatively understudied (Obiero et al. 2023). This asymmetry provides a rationale for concentrating further work on the Ethiopian reach of the system, namely the lower Omo, its floodplain and the delta, where the evidence base is thinnest and where management decisions are taken.

Socio-economically, critical data regarding the actual operational performance of large-scale irrigation are missing or obscured. While the Kuraz Sugar Development Project suffers documented conveyance losses of 30-50%, comprehensive, transparent data on actual water abstractions versus designed abstractions are withheld, rendering basin-wide water balance calculations imprecise. Furthermore, significant gender data gaps persist: no females are employed in any sub-basin IWRM context, women's participation in watershed management is described as "invisible," and gender-disaggregated data regarding the impacts of the "flooding paradox" (destructive unseasonal dam releases) on female-headed households are absent (Water and Land Resource Centre 2024d).

Together, these overlapping deficits reveal a basin where major infrastructural transformations have outpaced the institutional and scientific capacity to measure their impacts. Until the hydrometric network is rebuilt and coupled with empirical ecological monitoring, coupled-system modelling, and transboundary data-sharing, it would be difficult to transition reactive basin management into an adaptive form. These gaps bear directly on the confidence that can be placed in the estimated impacts reported in this review: confidence is highest for dam-driven hydrological mechanisms, moderate for governance and dam-impact interpretations, and lowest for the groundwater and atmospheric pathways and for the two irrigation-driven claims that remain unresolved, while the headline projections of fisheries decline and ATTZ contraction are empirically unvalidated for the post-Gibe III period. The basis for this gradation is set out in Sections 3.7 and 4.5.

1.9 Aims and Objectives

This review synthesizes the available academic and grey literature on the lower Omo, its floodplain and the Omo delta to examine how flow regulation, irrigation development, climate variability and land-use change are represented in the evidence base for this reach. It uses this literature to identify the main ecological functions, ecosystem services, causal pathways, SDG trade-offs and contested claims associated with transformation of the lower basin. Lake Turkana is treated as the receiving boundary downstream of the delta and is considered in terms of the inflow it receives, the evidence it provides on the consequences of altered inflow, and the transboundary obligations that follow; it is not treated as a study system in its own right. The review also highlights the evidence gaps and monitoring deficits that currently limit confident attribution, scenario assessment and environmental-flow specification for the lower Omo.

2. Methodology

2.1 Study Area and Physical Setting

The review focuses on the lower Omo, its floodplain and the Omo delta, and treats the wider Omo-Gibe-Lake Turkana system as the endorheic unit within which that reach sits. The Gibe headwaters in the Ethiopian highlands and the middle-reach gorges are considered as upstream drivers of flow, sediment and nutrient delivery to the lower basin, while Lake Turkana and the lake's additional Kenyan watersheds are considered as the receiving boundary downstream of the delta. Because the system has no marine outlet, changes to flow, sediment and nutrient delivery in the upper and middle reaches are not exported but are ultimately expressed in the lower Omo, the delta and the lake, subject to attenuation within the lower catchment and the lake itself. The physical setting of this study area, together with the hydropower and irrigation developments within it, is described in Sections 1.1 to 1.3 and is not repeated here.

2.2 Conceptual Framing and Analytical Components

As the literature was synthesized and interconnected pathways emerged, the Flood Pulse Concept (Junk et al. 1989) was adopted as the central organizing framework, on the grounds that the seasonal flood pulse is the process through which the basin's hydrology, ecology and livelihoods are coupled. The framework is used to trace how current and projected interventions alter that pulse, and how those alterations propagate to lake-level and geochemical thresholds such as salinization risk, to ecological responses in primary productivity, fisheries and biodiversity, and to livelihoods and governance.

Four analytical components follow from this framing, and are referred to as such throughout the remainder of this report:

1. ecological function analysis, emphasizing the flood-pulse concept and the ATTZ;
2. hydrological process analysis, including climate variability, dam regulation, and irrigation abstraction;
3. ecosystem service assessment across provisioning, regulating, cultural, and supporting dimensions; and,
4. SDG alignment analysis, examining synergies and trade-offs.

2.3 Literature Sourcing and Search Strategy

The search strategy used an expansion approach, in which contextual keywords, conclusions, and citation tracking (forwards and backwards) served as nodes from which the evidence base was progressively expanded. The initial batch of peer-reviewed literature was retrieved from four academic databases: Scopus (primary), Web of Science, Google Scholar, and JSTOR. Boolean search strings were tailored to each database, and field limits were applied to Title, Abstract, and Keywords where permitted. The primary search strings are shown in Table 6.

Table 6. Primary search strings applied across the four academic databases.

Database	Search String
Scopus	TITLE-ABS-KEY ("Omo River" OR "Omo-Gibe" OR "Lake Turkana" OR "Turkana Basin") AND (hydrolog* OR ecolog* OR dam* OR fisher* OR irrigat* OR governance OR "climate change" OR "flood pulse")
Web of Science	TS=("Omo River" OR "Omo-Gibe" OR "Lake Turkana") AND TS=(hydrolog* OR ecolog* OR dam* OR irrigat*)
Google Scholar	"Omo Gibe basin" hydrology ecology dam fisheries
JSTOR	"Omo River" OR "Lake Turkana" AND dam OR irrigation OR ecology

Once themes within the literature were identified, thematic sub-searches were conducted using the supplementary keywords in Table 7.

Table 7. Supplementary keywords for thematic sub-searches.

Thematic Area	Supplementary Keywords
Atmospheric dynamics	"Turkana jet" OR "Turkana low-level jet" OR "rift valley circulation"
Governance frameworks	"Ethiopia water policy" OR "transboundary water governance" OR "CRGE"
Paleoenvironmental	"Lake Turkana" AND (sediment* OR palaeo* OR geochem*)
Fisheries & livelihoods	"Lake Turkana" AND (fish* OR livelihood* OR "flood recession" OR pastoral*)
Irrigation & water use	"Omo Valley" AND (irrigat* OR "sugarcane" OR "water abstraction")

Grey literature was retrieved through supplementary searches in Google and in document repositories such as Scribd, using strings including “Gibe III” OR “Koysha dam” OR “EEP report” OR “DAFNE project” OR “Energy outlook”.

From a scan to identify the most highly cited works across the initially identified documents, five papers were chosen to be evidence anchors across four basic domains (hydrological variability, ecological responses, geochemistry, and policy) (Table 8). These papers were selected so that each provided a quantitative foundation

that subsequent papers cited. All subsequent thematic searches were structured as expansions from these core papers:

Table 8. Evidence anchor papers, with the rationale for selection and the basic domain each anchors.

Reference	Rationale for Selection	Basic Domain
Avery & Tebbs (2018)	Comprehensive pre- and post-dam hydrological reference for the Omo River. Comprehensive accounting of the possible effects of the Omo hydropower cascade on the lower basin and Lake Turkana	Hydrological variability / Policy
Byrne et al. (2024)	Provides post-2020 empirical evidence of lake expansion across central East Africa, used throughout this review to qualify and, where contradicted, override the pre-2020 decline projections anchored by Avery & Tebbs (2018).	Hydrological variability
Kolding (1992)	Foundational information on lake Turkana, with information about ecological responses such as the fisheries-lake-level relationship for Lake Turkana	Ecological responses
Tebbs et al. (2020)	Satellite-derived primary productivity time series for Lake Turkana	Ecological responses
Yuretich & Cerling (1983)	Establishes the importance of geochemical buffering and provides salinization risk	Geochemistry
Velpuri & Senay (2012)	Water balance modelling under dam and irrigation scenarios	Hydrological variability

2.4 Eligibility Criteria

To select the most applicable and credible literature sources for the study, several eligibility criteria were established and applied consistently across academic and grey literature sources (Table 9):

Table 9. Inclusion and exclusion criteria applied to academic and grey literature.

Inclusion Criteria	Exclusion Criteria
Directly addresses the Omo-Gibe-Lake Turkana Basin or its sub-catchments	Studies focused solely on other East African Rift lakes or basins
Reports primary data, model outputs, or systematic analysis relevant to the four analytical components	Editorials, commentaries, or opinion pieces without an empirical or analytical basis
Covers any period from 1979 to 2026	Duplicate publications of the same dataset without novel analysis
Models or projections calibrated or validated with basin-specific data	Studies citing basin data only in passing, without basin-specific analysis
Grey literature with identifiable methodology or institutional authorship	Studies with no original data, model, or analytical framework

Applying these criteria to the search output produced the final evidence base of 139 documents, published between 1979 and 2026, with particular emphasis on the post-Gibe III era (2016-2026).

2.5 Thematic Categorization

Each document was categorized as per the thematic synthesis principles elaborated by Thomas and Harden (2008), through a deductive-inductive process where categories were refined in response to emerging evidence. Categorization was performed by a single reviewer, who resolved borderline assignments by judgement. By the end of the review, the literature corpus was categorized according to the following themes:

T1. Climate variability & drought;

T2. Hydrological modelling & water balance;

T3. Land use/land cover change (LULC);

T4. Governance, policy & political ecology;

T5. Fisheries & aquatic ecology;

T6. Dam impacts & reservoir operations;

T7. Irrigation & agricultural development;

T8. Water quality & geochemistry;

T9. Paleoenvironmental & geological;

T10. Atmospheric science/Turkana Jet;

T11. Ecosystem services;

T12. Transboundary cooperation & human rights;

T13. Livelihoods, food security & resilience;

T14. Project documents & grey literature;

T15. Riparian ecology & water quality;

T16. Wetland ecology & biodiversity.

2.6 Data Extraction

For each included document, a structured summary was completed through the recording of objectives, methods (study design, data sources, models, calibration metrics), key findings relevant to the four analytical components and limitations. Governance and socio-ecological evidence were assessed qualitatively, with conclusions requiring convergence across at least two of three independent source types such as quantitative monitoring data, qualitative narrative reporting, and policy or institutional documentation.

Important quantitative data (those that were central to the causal pathways), including methodological details (models used, emission scenarios, time horizons, bias-correction methods, calibration and validation metrics), and numerical results were extracted directly. Where data were reported only in figures, values were visually extracted; each figure was extracted twice to ensure the mean absolute difference between extractions was below 5%. Digitized values were then checked against the correlations and statistical values published in the source to verify accuracy. Three extractions were central to the core analytical outputs of this review: the ATTZ-amplitude scatter plot in Figure 7 of Gownaris et al. (2017), which links ATTZ extent to lake-level amplitude; chlorophyll-a concentrations from Tebbs et al. (2020); and seasonal flow regime values from Avery & Tebbs (2018).

2.7 Evidence Quality Assessment

Evidence quality was assessed at the thematic level using a five-dimension scoring framework. Each theme was scored from 1 to 5 for data availability, methodological rigor, temporal coverage, spatial coverage, and policy relevance, where 1 indicated very weak evidence, 2 weak evidence, 3 moderate evidence, 4 strong evidence, and 5 very strong evidence. The scores were used to compare the relative strength of evidence across themes, rather than to exclude documents from the review. Higher scores indicated themes supported by more complete datasets, stronger or better validated methods, broader temporal or spatial coverage, and clearer relevance to basin management or policy decisions. Lower scores indicated themes where the available evidence was sparse, geographically limited, methodologically uncertain, dependent on modelling assumptions or grey literature, or weakly linked to decision-making needs. The appraisal was therefore used as an interpretive tool to qualify confidence in the synthesis and to identify where further monitoring, validation, or targeted research is needed.

2.8 Graph and Tree Approach

Extracted data were organized using a graph-and-tree framework combining two complementary analytical logics to identify causal pathways, assess evidence strength, and characterize cross-pathway interactions.

In the graph framework, the full evidence base was treated as a dataset in its own right. Publication-year and thematic distributions were plotted to establish where the evidence is dense enough to support confident conclusions and where it remains too sparse to do so.

In the tree framework, causal pathways were traced across papers following how evidence branches from one domain into another. A causal link was established when: the originating paper reported a quantitative relationship or mechanism; the receiving paper cited that relationship as an input; and the direction and magnitude of the effect were consistent across studies. Each pathway was assigned a five-point confidence rating based on the quality and convergence of its supporting evidence. Six pathways (P1-P6) were derived. Their mechanisms and consequences are set out in Table 4; the drivers and thematic evidence base underpinning each are summarized in Table 10.

Table 10. Key drivers and affected themes for the six causal pathways derived from the evidence base. Pathway mechanisms and consequences are given in Table 4.

Pathway	Key Drivers	Affected Themes
P1 Dam regulation & flow alteration	Reservoir operation rules; Gibe I/II/III cascade; flow naturalization; flood-pulse suppression	T2 Hydrological modelling, T6 Dam impacts, T5 Fisheries, T7 Irrigation, T8 Water quality, T13 Livelihoods
P2 Irrigation abstraction & inflow reduction	Omo-Kuraz irrigation schemes consistent abstraction scheduling; irrigation efficiency; return flows	T7 Irrigation, T2 Hydrological modelling, T6 Dam impacts, T13 Livelihoods, T11 Ecosystem services
P3 Sediment trapping & nutrient retention	Reservoir sedimentation; sediment-yield modelling; downstream channel response; floodplain aggradation loss	T6 Dam impacts, T3 LULC, T5 Fisheries, T15 Riparian, T16 Wetland, T8 Water quality
P4 Groundwater recharge loss	Flood-pulse inundation extent; aquifer hydraulic properties; groundwater monitoring; irrigation-groundwater coupling	T2 Hydrological modelling, T6 Dam impacts, T7 Irrigation, T15 Riparian
P5 Turkana Jet evaporative amplification	Jet dynamics; moisture convergence; surface-energy budget; evaporation parameterization	T10 Atmospheric science, T1 Climate variability, T2 Hydrological modelling, T9 Palaeo
P6 Land-cover & climate feedback	LULC change; deforestation; albedo feedback; regional climate coupling; sediment-yield response	T3 LULC, T1 Climate variability, T9 Palaeo, T2 Hydrological modelling, T15 Riparian

Three interaction matrices were constructed: cross-pathway interconnections (1-10 scale), theme-pathway connections (1-5 scale), and cross-theme interconnections (1-10 scale). Each matrix was populated by counting the documents in the synthesis that explicitly linked the corresponding pair of pathways or themes, and the counts were then normalized.

2.9 Scenario Identification and Indicator Scoring

The four development scenarios, baseline pre-dam, current (Gibe III operational with expanding irrigation), negotiated compromise (DAFNE project), and full irrigation expansion, were inductively extracted from the literature. They were identified during thematic categorization, then mapped against the causal pathway network and cross-pathway interactions to assess their evidentiary connections. Scenarios with the strongest documented support were retained for analysis.

The baseline scenario was identified as the condition of least human disturbance that has sufficient documentary description: the pre-dam, pre-large-scale-irrigation state, extracted from the early hydrological record (Yuretich & Cerling, 1983; Avery & Tebbs, 2018). This scenario is characterized by an unregulated flood pulse, natural sediment and nutrient flux, and minimal evaporative amplification from land-cover change.

For each of the four scenarios, five indicators were assigned: 1) hydropower generation, 2) irrigation supply, 3) fish production, 4) recession agriculture, and 5) downstream livelihoods. Indicators were scored through a 5-point scale, where a score of 1 indicates that the indicator is projected to collapse relative to its baseline state; 5 indicates that the indicator is maximized. For productive endpoints such as hydropower or irrigation, a score of 5 represents full operational deployment, while a score of 5 for ecological and livelihood endpoints indicates that the baseline condition is preserved.

The five indicators are defined operationally as follows:

1. Hydropower generation: installed capacity in MW (pre-Gibe baseline = 0 MW; current = Gibe III at 1,870 MW).
2. Irrigation supply: cumulative irrigated area in ha (baseline = small traditional footprint; current ≈ 50,000 ha; full expansion = 150,000-200,000 ha; Avery & Tebbs, 2018).
3. Fish production: relative biomass and fishery production associated with the lower Omo river, floodplain and reservoir systems relative to the pre-development baseline, informed by available fisheries and ecological evidence. This indicator represents fisheries-dependent ecosystem services within the Ethiopian reach rather than Lake Turkana fisheries alone.
4. Recession agriculture: hectares of flood-recession cultivation sustained by the natural flood pulse.
5. Downstream livelihoods: a composite of fish availability, recession-cultivable land, grazing access and river-dependent livelihood opportunities within the lower Omo floodplain and delta.

Scores were assigned through four steps. First, relevant evidence was identified for each scenario-indicator pair; the primary quantitative anchors are the ATTZ-amplitude relationship (Gownaris et al. 2017), chlorophyll-a trends (Tebbs et al. 2020), the seasonal flow regime (Avery & Tebbs, 2018), and multi-stakeholder modelled outcomes (Giuliani et al. 2022). Second, where quantitative projections were available, values were mapped to the 1-5 scale using threshold bands: for fish production, relative biomass ≥80% = 5, 50-80% = 4, 30-50% = 3, 10-30% = 2, <10% = 1; analogous bands were applied to the other indicators. Third, where evidence was qualitative or partial (notably recession agriculture and downstream livelihoods under DAFNE), scores were assigned by judgement. Finally, the 20 scores were checked for internal consistency across scenarios.

2.10 SDG Mapping Method

Sustainable Development Goal (SDG) alignment was conducted in two stages. First, all 17 SDGs were screened against the evidence base; a goal was retained if at least one quantitative threshold in the considered literature corresponded to a measurable SDG target. This screening produced nine relevant goals: SDG 1 (No Poverty); SDG 2 (Zero Hunger); SDG 6 (Clean Water and Sanitation); SDG 7 (Affordable and Clean Energy); SDG 13 (Climate Action); SDG 14 (Life Below Water); SDG 15 (Life on Land); SDG 16 (Peace, Justice and Strong Institutions); and SDG 17 (Partnerships for the Goals). SDGs not retained (SDG 3 Good Health and Well-being; SDG 4 Quality Education; SDG 5 Gender Equality; SDG 8 Decent Work; SDG 9 Industry and Innovation; SDG 10 Reduced Inequalities; SDG 11 Sustainable Cities; and SDG 12 Responsible Consumption) had no directly measurable threshold represented in the basin literature, though several appear as second-order consequences in the synthesis.

Second, evidence was mapped to specific SDG targets and goal-to-goal interactions were classified using the Nilsson et al. (2016) typology, which defines seven interaction categories: indivisible, reinforcing, enabling, consistent, constraining, counteracting, and cancelling. For each theme-SDG pair, an alignment score from 1 (low) to 5 (high) was assigned based on the number and quality of documents connecting the theme to a measurable SDG target. A score of 5 indicates that the theme contains multiple quantitative studies directly addressing the SDG target; while 1 indicates the theme touches the SDG only tangentially.

2.11 Agreement, Disagreement and Contested-Claims Analysis

At the theme-document level, each document's contribution to the 16 thematic categories was coded as Agree, Partial/ambiguous, or Disagree based on its alignment with the modal finding for that theme. Agree indicated directional consistency and magnitude within the range reported across the evidence base; Partial/ambiguous referred to context-dependent or non-committal findings; Disagree indicated directional inconsistency or explicit contestation. With 359 theme-document pairings from 139 documents, each document contributed an average of 2.6 pairings.

Contested claims were considered as policy-relevant propositions about the basin on which the evidence base does not "speak with one voice". Ten such claims were extracted from the pathway identification, and for each claim, documents were classified as supporting, contradicting, or ambiguous based on their conclusions.

Contested claims were limited to causal claims, in the form of “X causes Y” or “X increases Y by Z%”. Claims in this form were retained only where they carried direct implications for basin management or development decisions, were quantitative or had a clear qualitative threshold, and were addressed by at least three documents in the evidence base. The ten claims retained on this basis are listed in Table 11, together with the causal pathway or pathways that each concerns. Several claims span more than one pathway; where they do, the pathway listed first is the primary one.

The propositions listed below are contested claims drawn from the literature for evaluation against the evidence base, not confirmed findings of this review; each is assessed for the balance of supporting, contradicting and ambiguous evidence in Section 3.7.

Table 11. The ten contested claims and the causal pathway or pathways that each concerns, primary pathway listed first.

Claim	Proposition	Pathways
C1	Gibe III dam reduced Lake Turkana water level by >1.5 m	P1 Dam regulation & flow alteration; P2 Irrigation abstraction & inflow reduction
C2	Dam cascade suppressed the Omo flood pulse by >80%	P1 Dam regulation & flow alteration
C3	Irrigation abstraction permanently reduces lake inflow	P2 Irrigation abstraction & inflow reduction
C4	Sediment trapping by dams reduces delta fertility	P3 Sediment trapping & nutrient retention; P1 Dam regulation & flow alteration
C5	Dam operation caused fishery collapse in Lake Turkana	P1 Dam regulation & flow alteration; P3 Sediment trapping & nutrient retention
C6	Turkana Jet amplifies lake evaporation by 16-37%	P5 Turkana Jet evaporative amplification; P6 Land-cover & climate feedback
C7	Irrigation expansion increases household food security	P2 Irrigation abstraction & inflow reduction; P1 Dam regulation & flow alteration
C8	Groundwater recharge depends on flood pulse inundation	P4 Groundwater recharge loss; P1 Dam regulation & flow alteration
C9	Land-cover change in upper catchment increases sediment yield	P6 Land-cover & climate feedback; P3 Sediment trapping & nutrient retention
C10	Negotiated compromise pathway outperforms full irrigation expansion	Cross-cutting: governance and transboundary trade-offs across P1-P6

Each of the 139 documents was coded against given to documents that are more recent (post dam construction) and where analyses are based on primary data rather than modelling

The S, C and Amb counts were aggregated for each claim and an overall confidence rating for each claim was obtained. A claim is rated "Contested (majority supporting)" if the number of S documents exceeds the number of C documents and the S documents constituted at least half of all the documents across S,C, and Amb. A claim is rated "Unresolved" if the C documents equal or exceed the S documents, or if the engaging evidence is so sparse (fewer than 10 engaging documents) and so evenly split that no majority position can be identified with confidence.

A three-way cross-walk matrix was constructed to link each of the 16 thematic categories to its primary causal pathway and its primary contested claim. For each theme, the cross-walk records the theme-to-pathway strength (along the five-point scale described in Section 2.8), and the theme-to-claim link level (along a three-point scale, where 3 = primary anchor, 2 = secondary, 1 = tertiary). The link level was assigned on the basis of how directly the theme's evidence base engages the claim: 3 for a theme whose documents routinely take a position on the claim; 2 for a theme whose documents occasionally engage the claim; and 1 for a theme whose documents are relevant to the claim but rarely take an explicit position.

3. Results

This section reports the meta-analysis of the evidence base: the temporal, geographic, thematic, and methodological characteristics of the 139 documents retained after screening, and the analytical structures (causal pathway network, scenario analysis, SDG mapping, and contested-claims cross-walk) derived from them.

3.1 Composition of the Evidence Base

Of the 139 documents, 73 (53%) were published between 2020 and 2026, and 28 (20%) between 2015 and 2019 (Figure 3). Only 7 documents (5%) predate 1990. The post-2015 growth is driven primarily by hydrological modelling, climate projection studies, and governance analyses, while empirical ecological monitoring remains notably sparse after 2019.

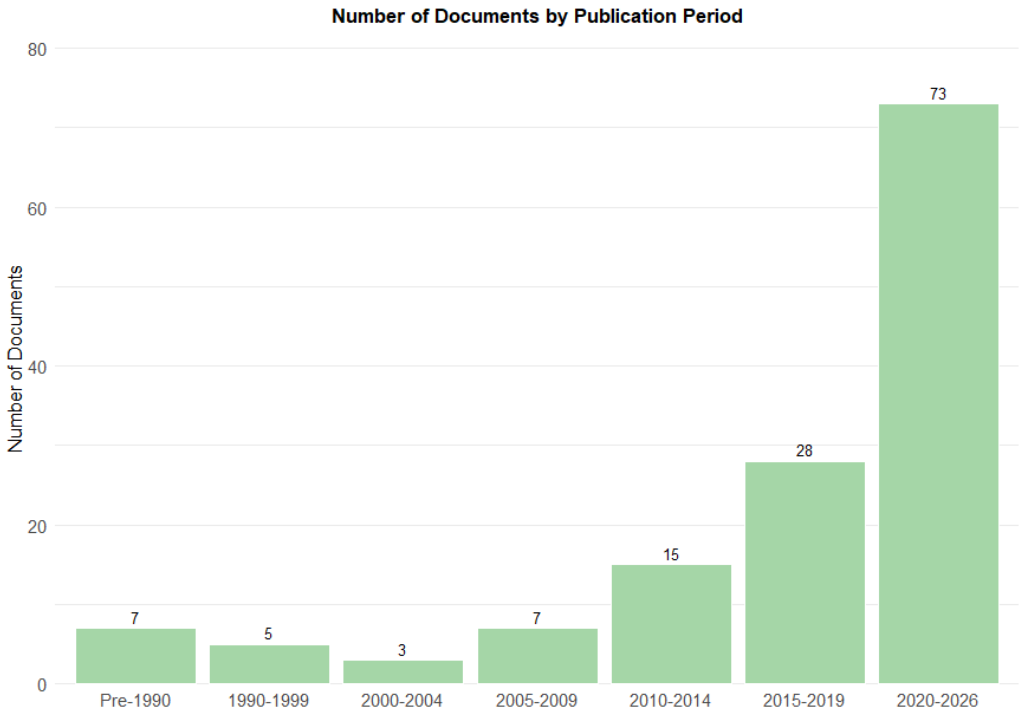

Figure 3. Bar chart showing the number of publications per 10-year period among the 139 documents retained after screening.

The thematic composition also shifts across periods: Pre-2010 literature is dominated by foundational geochemistry, sedimentology, and early dam impact assessments (Figure 4). The 2010-2014 period sees climate projection studies and water balance modelling emerge. Post-2015, the evidence base diversifies: atmospheric science (Turkana Jet) and governance analyses grow rapidly, while hydrological modelling continues to accumulate. Previously separate strands of evidence converge in the literature published after 2020, as exemplified by the application of the DAFNE project's multi-stakeholder modelling platform in Giuliani et al. (2022) and the RIFTJET field campaign investigating the Lake Turkana Jet (Munday et al. 2024).

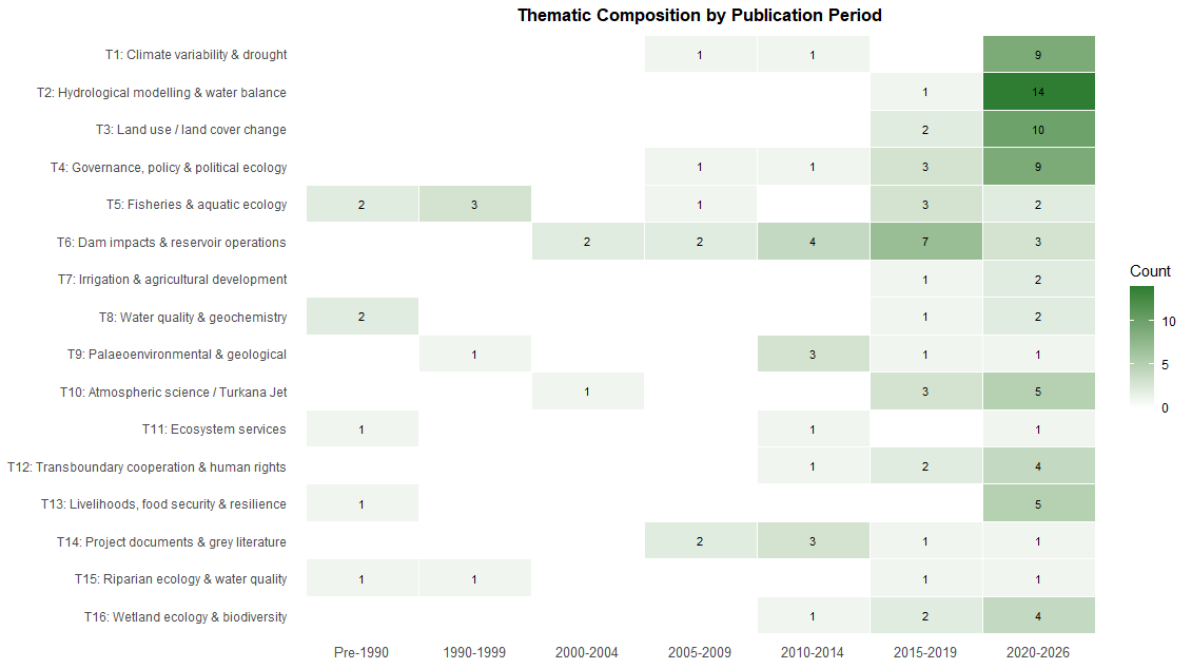

Figure 4. Matrix illustrating the distribution of themes (T1-T16) across ten-year publication periods.

When the primary geographic focus of each document is examined, basin-wide studies and Lake Turkana (Kenya) are the most frequently addressed regions, each covered by 32 documents (23% of the evidence base) (Figure 5). The Middle Omo (Gibe basin), home to the Gibe hydropower cascade, follows with 26 documents (19%). The transboundary perspective accounts for 21 documents (15%). The Lower Omo Valley is the focus of 16 documents (12%), while the Upper Omo (Ethiopian Highlands) is the focus of 12 documents (9%).

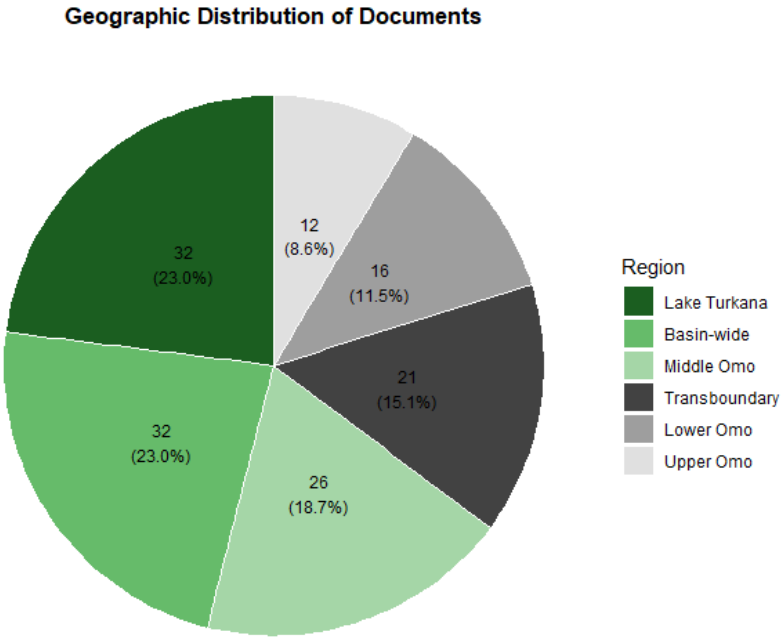

Figure 5. Primary geographic focus of the 139 documents within the Omo-Gibe basin.

The “Basin-wide” slice captures hydrological-modelling, climate-variability, and paleoenvironmental research that treats the Omo-Turkana system as an integrated endorheic unit, and anchors the quantitative studies categorized under “Hydrological modelling & water balance” (15 documents) and “Climate variability & drought” (11 documents). The “Lake Turkana” slice captures the fisheries, wetland ecology, atmospheric science, and water-

quality research focusing on the lake's role as a terminal sink, and is dominated by "Fisheries & aquatic ecology" (11 documents), "Atmospheric science / Turkana Jet" (9 documents), "Wetland ecology & biodiversity" (7 documents), and "Water quality & geochemistry" (5 documents). The "Middle Omo" slice (19%) is dominated by dam-impacts and project-document evidence concentrated around the Gibe cascade. The "Transboundary" slice (15%) is anchored by governance, policy, and human-rights literature that explicitly frames the basin as a shared Ethiopian-Kenyan system. The "Lower Omo Valley" slice (12%) is studied for irrigation and livelihood impacts, rather than as an ecological or hydrological system in its own right. This imbalance in the inherited evidence base is one of the reasons this review concentrates its own analysis on the lower Omo, its floodplain and the delta, as set out in Section 1.9, rather than reproducing the lake-centric emphasis of the wider literature. Similarly, the "Upper Omo (Ethiopian Highlands)" slice (9%) is studied almost exclusively through the lens of land-use / land-cover change, with headwater hydrology and upland ecology essentially unstudied.

Cross-tabulating the 16 thematic categories against the six geographic foci shows how unevenly the two axes overlap (Figure 6). Hydrological and dam-impact research is distributed across the Basin-wide, Middle Omo and Transboundary columns, whereas fisheries, wetland ecology and atmospheric science are concentrated almost entirely in the Lake Turkana column. Large parts of the matrix are empty: the Upper Omo has substantive coverage in only one theme, and no theme other than irrigation and livelihoods is well represented in the Lower Omo Valley.

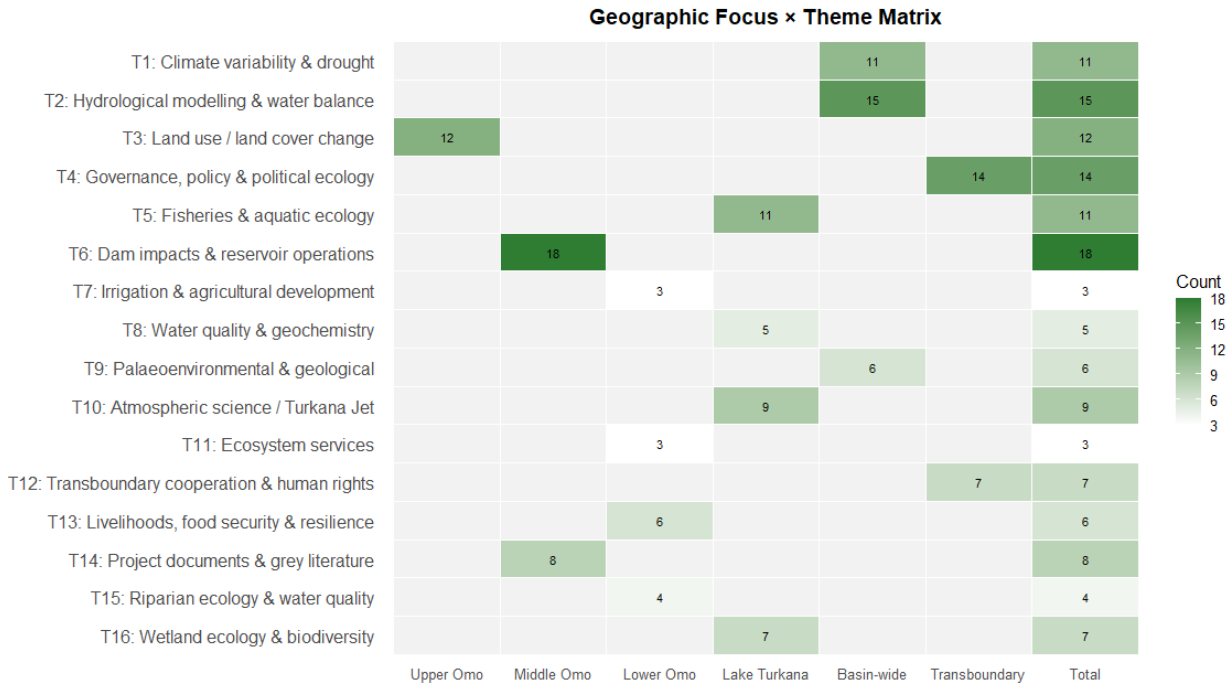

Figure 6. Cross-tabulation of the 16 thematic categories against the six primary geographic foci within the Omo-Gibe catchment, for the 139 documents.

The evidence base employs a diverse range of methodological approaches, as presented in Figure 7:

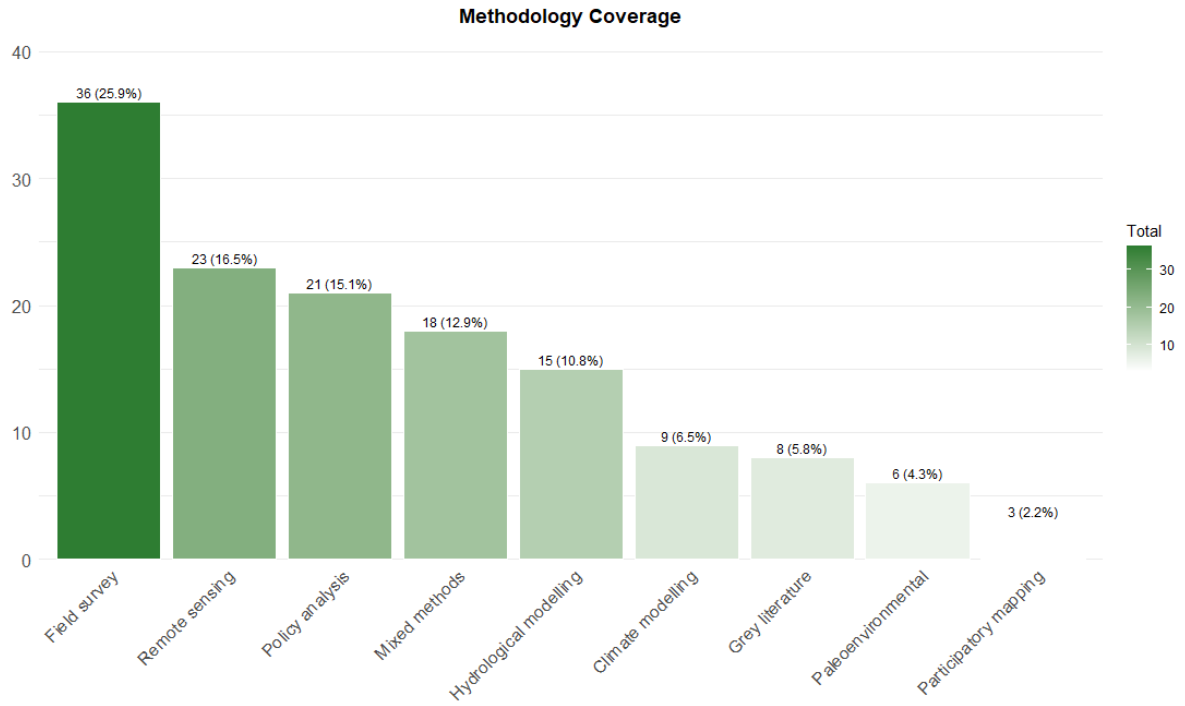

Figure 7. Primary methodological approaches employed across the 139 documents.

The most frequent primary methodology was “Field survey” (36 documents, 26% of the evidence base). “Remote sensing” followed with 23 documents (17%), anchored by the LULC-change and climate-variability literature. Policy analysis accounts for 21 documents (15%), concentrated in the governance and transboundary cooperation themes. Mixed methods (18 documents, 13%) and hydrological modelling (15 documents, 11%) are dominated by the dam-impacts and reservoir-operations evidence around the Gibe cascade. The prevalence of field survey and remote sensing literature may reflect both the unavailability of data when the relevant study was conducted and the high emphasis on quantifying hydrological and ecological change. The low representation of participatory mapping (3 documents, 2%) highlights a persistent lack of integrative, multi-stakeholder research.

When each document is assigned to a single primary theme, “Dam impacts and reservoir operations” is the most frequent (18 documents, 13% of the evidence base), followed by “Hydrological modelling and water balance” (15 documents, 11%) (Figure 8). This classification identifies each document’s dominant thematic orientation only; overlaps between themes, including modelling studies used to assess dam impacts and reservoir operations, are captured in the cross-theme and theme-pathway analyses presented later in the Results section. Thematic analysis reveals an asymmetry in the evidence base, with ecological and water-resource endpoints that are directly affected by upstream interventions being underrepresented (“Ecosystem services”: 3 documents; “Irrigation and agricultural development”: 3 documents; “Riparian ecology and water quality”: 4 documents; and “Water quality and geochemistry”: 5 documents). Moderately represented themes (“Project documents and grey literature”; “Transboundary cooperation and human rights”; and “Wetland ecology and biodiversity”) form a cluster that is sufficient for qualitative synthesis but likely insufficient for quantitative meta-analysis.

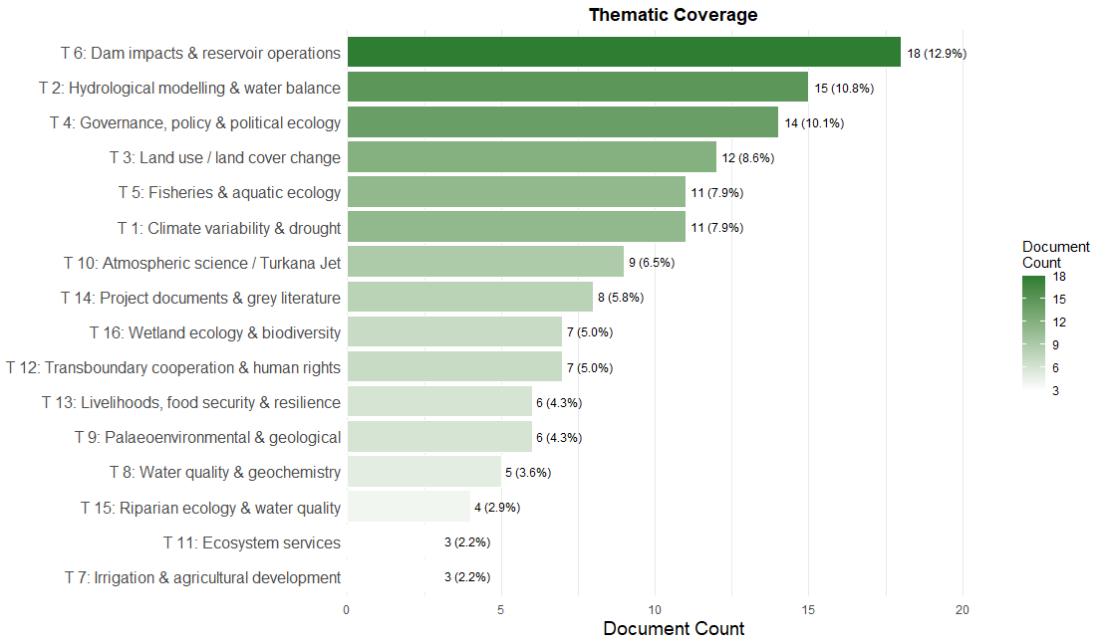

Figure 8. Thematic coverage (T1-T16) across the 139 documents included in the evidence base.

3.2 Evidence Density

Evidence density was obtained to understand which themes can support high-confidence conclusions and where remaining gaps constrain confidence (Figure 9). For each theme, a single overarching evidence type was considered. “Hydrological modelling and water balance”, “Land use / land cover change”, and “Climate variability & drought” constituted the densest cluster, with a rapid growth in publications post-2016 coinciding with the Gibe III commissioning. Governance literature is well represented but remains sparse relative to hydrological work throughout the review period, and no empirical ecological monitoring studies, as distinct from model projections, were identified post-2017.

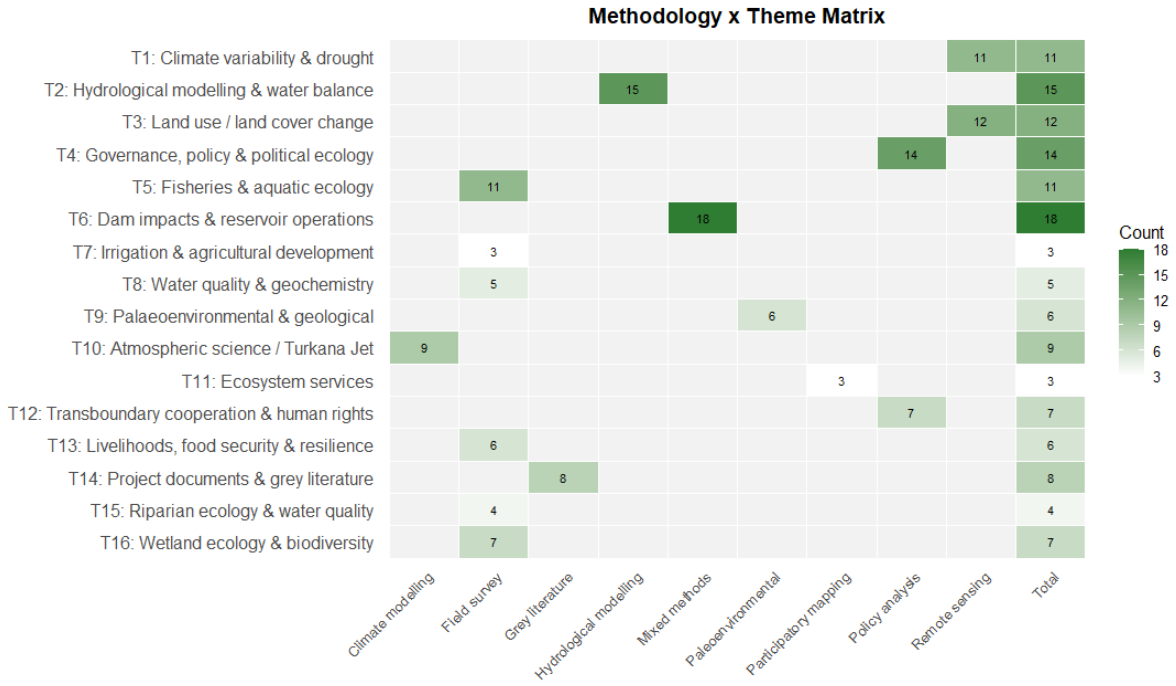

Figure 9. Frequency distribution of evidence density by primary evidence types across 16 thematic categories (T1-T16).

3.3 Cross-Theme Interconnection and Evidence Quality

The strongest interconnections are between “Climate variability and drought” and “Hydrological modelling and water balance”; “Hydrological modelling and water balance” and “Fisheries and aquatic ecology”; “Transboundary cooperation” and “Riparian ecology and water quality”; and “Dam impacts and reservoir operations” and “Irrigation and agricultural development” (Figure 10). This interconnection matrix reveals notable asymmetries within the evidence base:

Themes relating to hydrology and dam impacts are densely interconnected, indicating that literature within those domains has a cross-cutting focus. In contrast, themes relating to atmospheric science are interconnected with only a few other themes, despite the Lake Turkana Jet physically coupling atmospheric processes to lake evaporation. Similarly, documents within themes related to governance are lightly interconnected, despite governance being the policy lever through which hydrological findings could be acted upon. The weak interconnections between ecosystem services and riparian ecology and water quality, and ecosystem services and wetland ecology and biodiversity, suggests ecosystem services studies have not embedded riparian- or wetland-specific ecological and water-quality aspects in their approach.

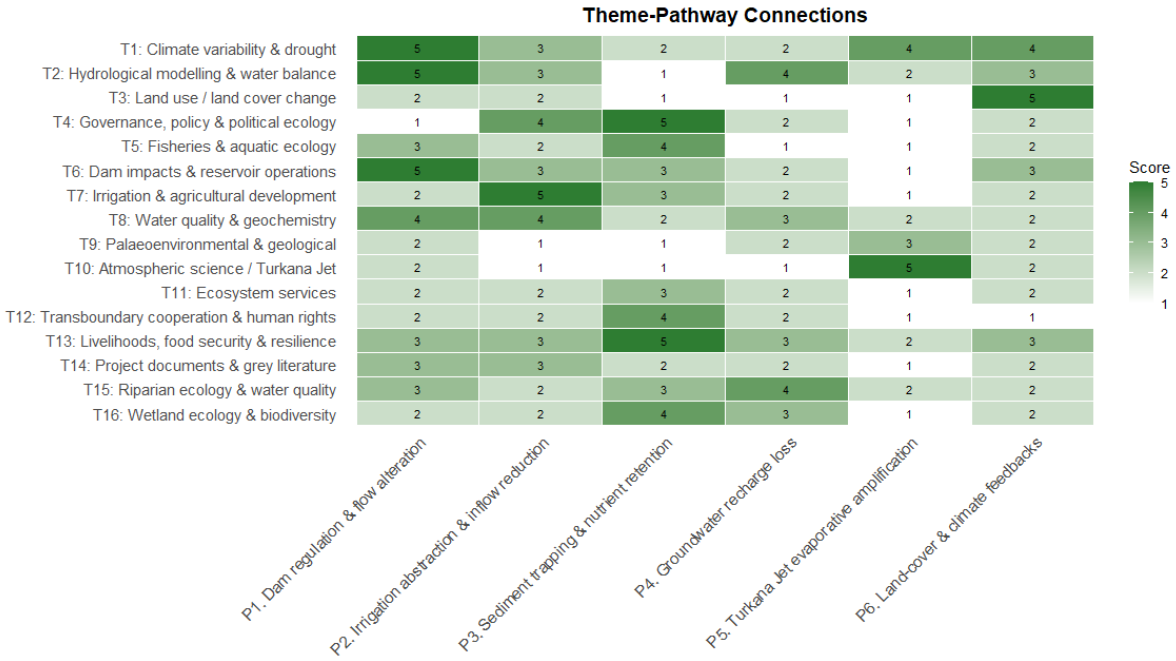

Figure 10. Cross-theme co-occurrence matrix for the 16 thematic (T1-T16) categories, based on the 139 publications included in the review.

The evidence-quality assessment showed uneven strength across themes. Hydrological modelling and water-balance studies scored highest overall, reflecting comparatively strong methodological rigor, data availability, temporal coverage, and policy relevance. Fisheries and aquatic ecology, dam impacts, and climate variability also showed relatively strong evidence, although spatial coverage and direct post-regulation monitoring were more limited. Governance, policy, and political-ecology evidence was moderately strong, particularly in policy relevance and spatial breadth, but was less consistently supported by quantitative monitoring data. Land-use/land-cover change, atmospheric science related to the Turkana Jet, transboundary cooperation and human-rights literature, project documents and grey literature, and wetland ecology showed more uneven quality, with lower scores for data availability, methodological rigor, or spatial coverage. Overall, the appraisal indicates that confidence is strongest for hydrological and fisheries-related pathways, moderate for governance and dam-impact interpretations, and lower for pathways depending on groundwater dynamics, atmospheric feedback, wetland responses, and grey-literature-based claims.

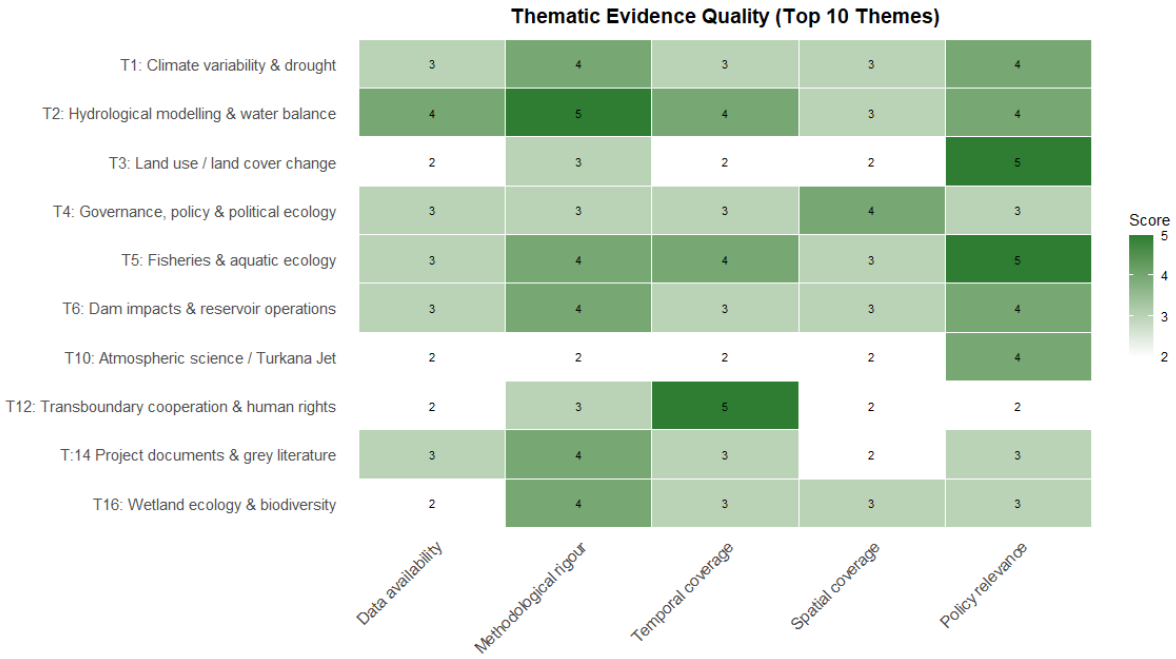

Figure 11. Thematic evidence quality assessment across five dimensions for the 139 considered literature (only the top 10 themes are shown).

3.4 Causal Pathways and Cross-Pathway Interactions

Mapping the 16 thematic categories onto the six causal pathways gives the theme-pathway matrix in Figure 12, in which each of the 96 cells records the strength of the evidence linking a theme to a pathway on the five-point scale defined in Section 2.8. Pathway 1 (Dam regulation) is the most densely connected pathway, with strong contributions from themes related to climate variability and water balance. Pathway 2 (Irrigation abstraction) is anchored by documents categorized within themes relating to irrigation, water quality and geochemistry, and governance. Pathway 3 (Sediment/nutrient) is anchored by documents across themes related to governance, fisheries, livelihoods, and wetlands.

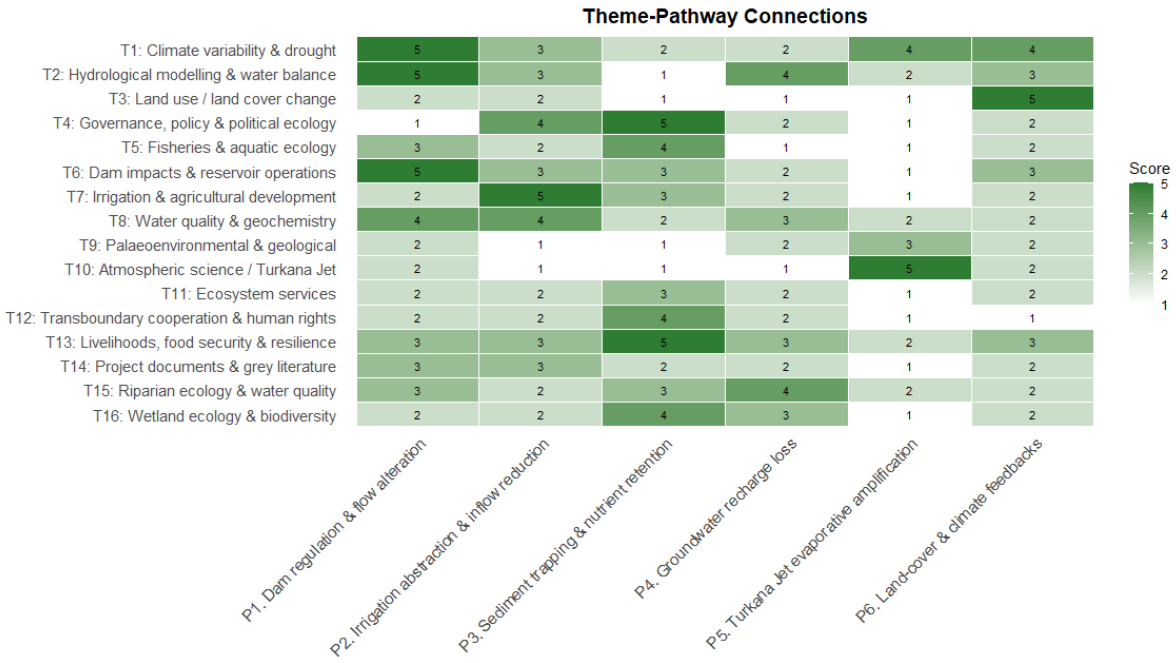

Figure 12. Theme-pathway matrix illustrating the strength of evidence supporting associations between the 16 thematic categories and six causal pathways, assessed using a five-point scale.

The theme-pathway interconnections in Figure 12 have been further classified into three categories: Well-covered (theme-pathway connection strength 4-5, indicating that the theme provides a strong evidence base for that pathway), Under-covered (strength 2-3, indicating that the theme provides contextual but not dominant evidence), and Gap (strength 0-1, indicating that the theme's evidence base does not substantively contribute to that pathway). Out of the 96 theme-pathway interactions, 18 are classified as Well-covered (18.8%), 58 as Under-covered (60.4%), and 20 as Gaps (20.8%). The pathways with the most Well-covered themes are Pathway 3 (Sediment trapping and nutrient retention) with 5 well-covered themes, and Pathway 1 (Dam regulation and flow alteration) with 4 well-covered themes. The pathways with the fewest Well-covered themes are Pathway 4 (Groundwater recharge loss) and Pathway 5 (Turkana Jet evaporative amplification), each with only 2 well-covered themes, a pattern that further confirms the persistent evidence gaps on groundwater and on the atmospheric aspects of the basin's water balance.

The themes with the most gaps across the six pathways are "Land use / land cover change" (3 gaps out of 6), and "Atmospheric science / Turkana Jet" (3 gaps out of 6), followed by four themes tied at 2 gaps each: "Governance, policy and political ecology"; "Fisheries & aquatic ecology"; "Paleoenvironmental and geological"; and "Transboundary cooperation and human rights".

The gaps for P5 (Turkana Jet) mean that basin-wide water-balance models cannot yet attribute lake-level decline to its atmospheric component with confidence. Similarly, the P4 (Groundwater) gap means that important aspects, such as the role of groundwater in buffering dry-season flows under dam regulation, are poorly studied, which limits the ability to design irrigation abstractions that avoid depleting the groundwater reserve on which downstream livelihoods depend. Finally, the cluster of gaps in the "Atmospheric science / Turkana Jet", "Land use / land cover change", and "Transboundary cooperation and human rights" rows means that the cross-scale interactions most relevant to basin-wide governance (jet dynamics, headwater land-use change, riparian-state cooperation) are precisely the interactions for which the evidence is thinnest. Of the documented management alternatives, only the DAFNE negotiated pathway (Giuliani et al. 2022) explicitly engages with these cross-scale gaps.

3.5 Scenario Analysis

The Baseline cluster is dominated by strong ecological and livelihood indicators (Fish production, Recession agriculture and Downstream livelihoods) and comparatively low hydropower and irrigation indicators. The Current and Full Irrigation Expansion pathways display the opposite pattern, whereas the Negotiated DAFNE pathway occupies an intermediate position across the five indicators, reflecting an attempt to balance production objectives with maintenance of floodplain ecosystem services and livelihoods. Figure 13 summarizes the expected direction and relative magnitude of trade-offs across six outcome categories—hydropower generation, irrigation supply, fish production, recession agriculture, lake ecology and downstream livelihoods—under the four development scenarios considered in this review.

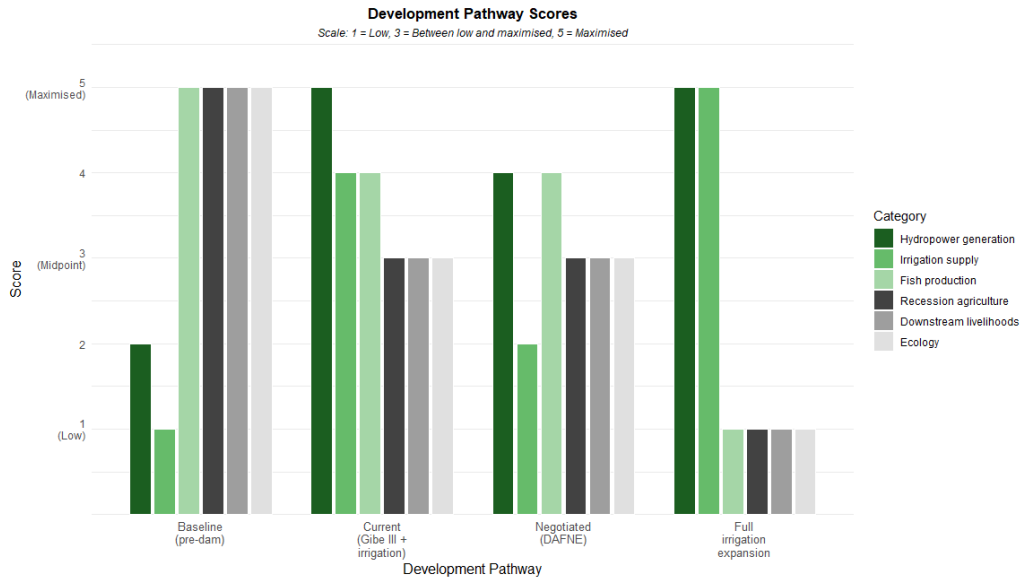

Figure 13. Scenario trade-off matrix comparing performance across six outcome categories—hydropower generation, irrigation supply, fish production, recession agriculture, lake ecology and downstream livelihoods—under four development scenarios.

3.6 SDG Mapping

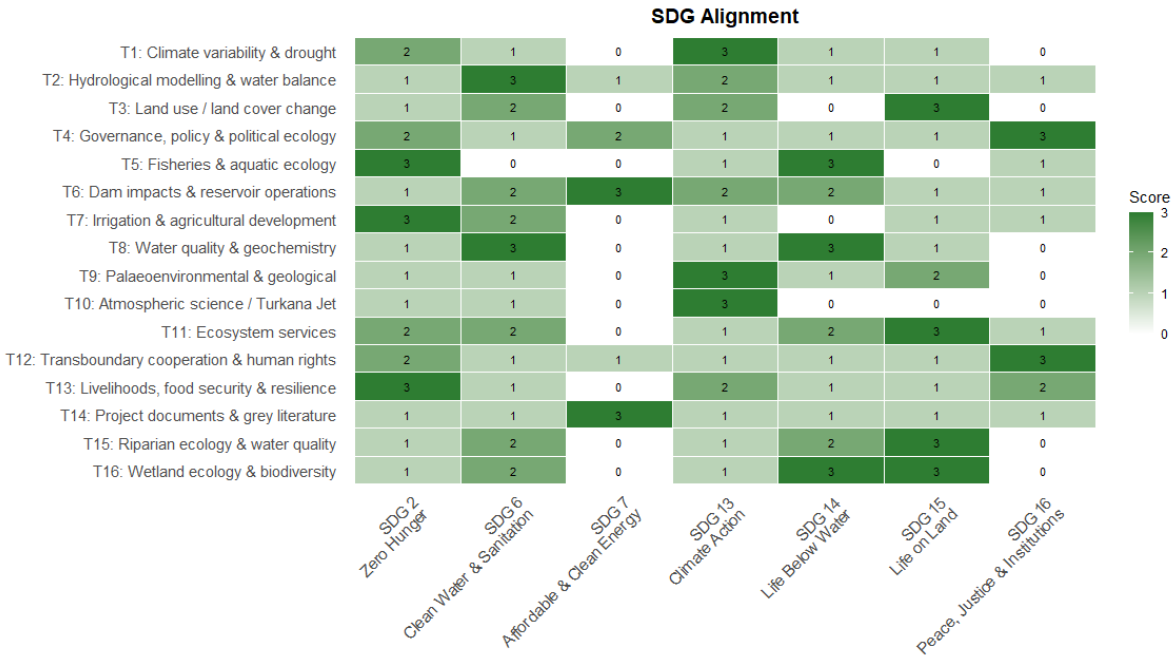

Figure 14. Alignment matrix of each relevant SDG against the 16 thematic categories (scores 0–3).

Figure 14 shows that the strongest single alignment is between “Hydrological modelling and water balance” and SDG 6 (Clean Water), "Climate variability and drought" and SDG 13 and between “Governance, policy and political ecology” and SDG 16 (Peace and Justice). Because the energy dimension of the basin is almost entirely framed through hydropower, SDG 7 (Clean Energy) has a narrow evidence base, primarily related to “Dam impacts and reservoir operation”. SDG 14 (Life Below Water) is supported by themes relating to Fisheries, Riparian ecology, and Wetland ecology. However, the evidence supporting these themes has been flagged as sparse in the evidence density matrix presented in Figure 9. This is critical, as SDG 14 and SDG 2, which are empirically at risk within the basin, do not have a comprehensive evidence base.

The four SDGs with the highest total alignment score are SDG 6, SDG 13, SDG 2 and SDG 16. SDG 6 (Clean Water) is dependent on documents categorized within themes related to Hydrological modelling, Dam impacts, and Water quality. SDG 13 (Climate Action) is carried by themes related to Climate variability and Atmospheric science, with secondary contributions from Paleoenvironmental and Hydrological modelling. SDG 2 (Zero Hunger) is carried by themes relating to Livelihoods, Fisheries, and Irrigation. SDG 16 (Peace and Justice) is carried almost entirely by themes relating to Governance and Transboundary cooperation, which exposes the thinness of the institutional-analysis evidence base. Figure 13 therefore suggests that interventions targeting SDG 16 should be prioritized for evidence-building, because the governance cluster is small relative to the magnitude of the trade-offs that it must mediate and modulate.

3.7 Contested Claims

The basin literature contains no uncontested quantitative claim, with every one of the 10 claims having at least one supporting and one contradicting or ambiguous document (Figure 15). The two claims with the highest total engagement, C8 (Groundwater recharge depends on flood pulse inundation, 25 documents) and C4 (Sediment trapping by dams reduces delta fertility, 24 documents), are both rated ‘Contested (majority supporting)’, indicating that while the dominant position is supportive, a substantive contradicting literature exists. In contrast, the two claims rated ‘Unresolved’: C3 (Irrigation abstraction permanently reduces lake inflow, 8 documents, 3 supporting / 4 contradicting / 1 ambiguous) and C7 (Irrigation expansion increases household food security, 10 documents, 4 supporting / 5 contradicting / 1 ambiguous), are the only ones where contradicting literature exceeds supporting literature, marking the two most policy-relevant uncertainties in the basin evidence base. This pattern is reflected in the stacked bar chart: the literature is most contested on the hydrological and ecological consequences of dam operation (C1, C2, C4, C5, C8, all with ≥19 engaging documents and majority-supporting verdicts), and least contested on the negotiated-pathway claim C10 (14 documents, 11 supporting, 1 contradicting, 2 ambiguous). Notably, the two Unresolved claims (C3 and C7) are precisely those where irrigation is the upstream driver, indicating greater confidence in dam-driven than irrigation-driven change. The high ambiguous counts on C5 (Dam operation caused fishery collapse, 6 of 12 engaging documents) and C8

(Groundwater recharge depends on flood pulse, 7 of 25) further signal that even where a majority position exists, the underlying evidence is fragmented across modelling, observational, and qualitative studies that do not always agree on magnitude or mechanism. A related limitation is that the claim-tallying method (Section 2.11) counts pre-construction predictive documents and post-construction observational documents as equally weighted supporting or contradicting evidence; re-weighting to privilege post-construction primary observation over pre-construction prediction should be treated as a priority methodological refinement.

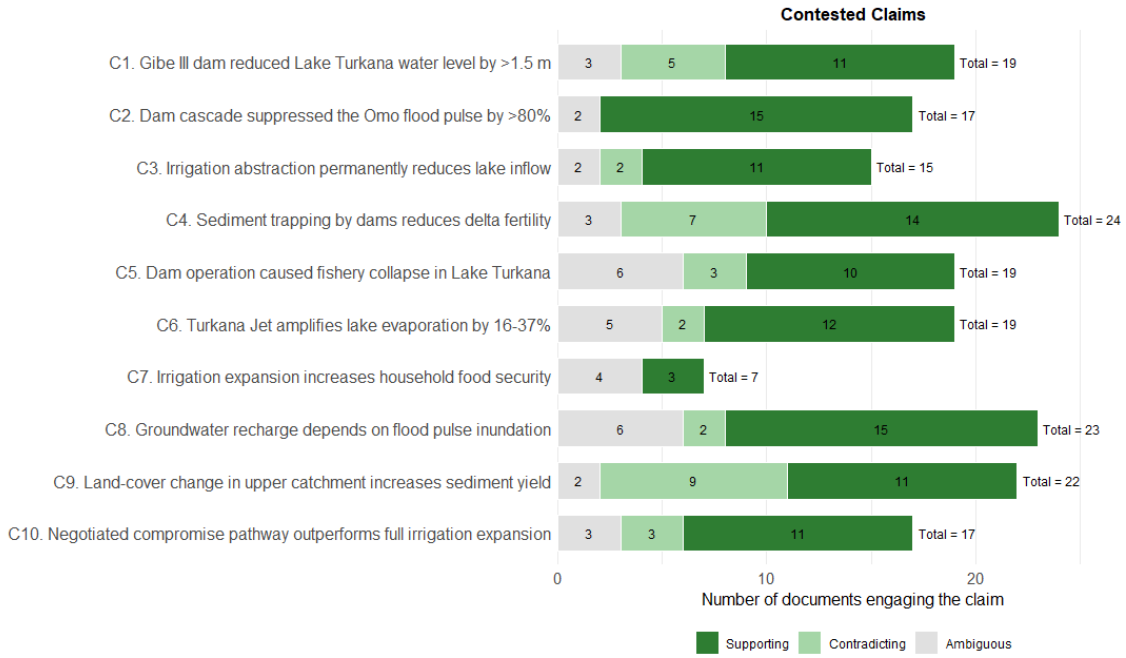

Figure 15. Engagement of the evidence base with the ten contested causal claims.

Two further divergences qualify the amplitude threshold on which the conclusions in Section 4.1 rest, and neither is captured by the ten claims. The first is between the peer-reviewed literature and documentation produced by or for the project developer, Ethiopian Electric Power (EEP). The Koysha basic design study, prepared for EEP by its design consultant Studio Pietrangeli, concludes that reservoir filling will lower Lake Turkana by approximately 0.9 m — a figure obtained by dividing the impounded volume by the lake surface area at the start of impounding (6,500 Mm^3 ÷ 7,300 km^2) — and characterizes this as comparable to the lake's average seasonal oscillation of about 1 m and well within the range of natural fluctuation (Studio Pietrangeli 2016); the ESIA main report similarly states that the project will not reduce annual flow to the lake (Ethiopian Electric Power 2016b). The same ESIA nonetheless specifies the regulated amplitude of approximately 0.3 m from which the projected 75% ATTZ contraction follows (Ethiopian Electric Power 2016a; Gownaris et al. 2017; Avery and Tebbs 2018).

The second divergence is temporal, and bears on both positions equally. All of these figures were derived before the lake began to expand. Since 2019–2020 Lake Turkana has risen by several meters and gained roughly a tenth of its surface area, and altimetric records now span a total range of some 9.4 m, placing recent levels well above the 363.4–363.7 m band assumed for the regulated case. Because level change scales inversely with surface area, expansion would in isolation damp seasonal amplitude further; because the underlying water balances projected decline rather than rise, their inflow assumptions are evidently in error in the opposite direction; and because the ATTZ-amplitude relationship was calibrated on shoreline bathymetry at the former level, the conversion from amplitude to littoral area no longer corresponds to the lake's present configuration. The direction of the combined bias cannot be determined from the available evidence. In the absence of empirical monitoring since 2017 (Section 4.5), it is not possible to obtain the actual amplitude change from satellite altimetry data; the 0.3 m amplitude and the 75% contraction that follows from it should be treated as unvalidated projections conditional on a lake state that no longer obtains, rather than as established quantities.

3.8 Three-Way Cross-Walk

Pathway 1 (Dam regulation & flow alteration) anchors 5 themes (T1, T2, T6, T8, and T14), and Pathway 3 (Sediment trapping & nutrient retention) anchors 6 (T4, T5, T11, T12, T13, and T16) (Figure 16). P3's integrative character is reflected in the claims that rest on it: claim C4 is anchored on P3 directly, and C5 draws on it as a secondary pathway alongside P1. C7, by contrast, is anchored on P2 (irrigation abstraction and inflow reduction), and C10 is not tied to a single pathway, being cross-cutting across P1-P6. Claim C1 (T2 and T6) is the most cleanly anchored. The chart also shows a coherent evidence-to-claim-to-mechanism structure, with every theme linked to a primary pathway and at least a tertiary contested claim, except for T9 (Paleoenvironmental &

geological) and T14 (Project documents & grey literature). P5/P6 themes (T3, T9, T10) anchor claims C6 and C9, tied to atmospheric and upper-catchment dynamics, while P2 anchors only T7 (Irrigation & agricultural development).

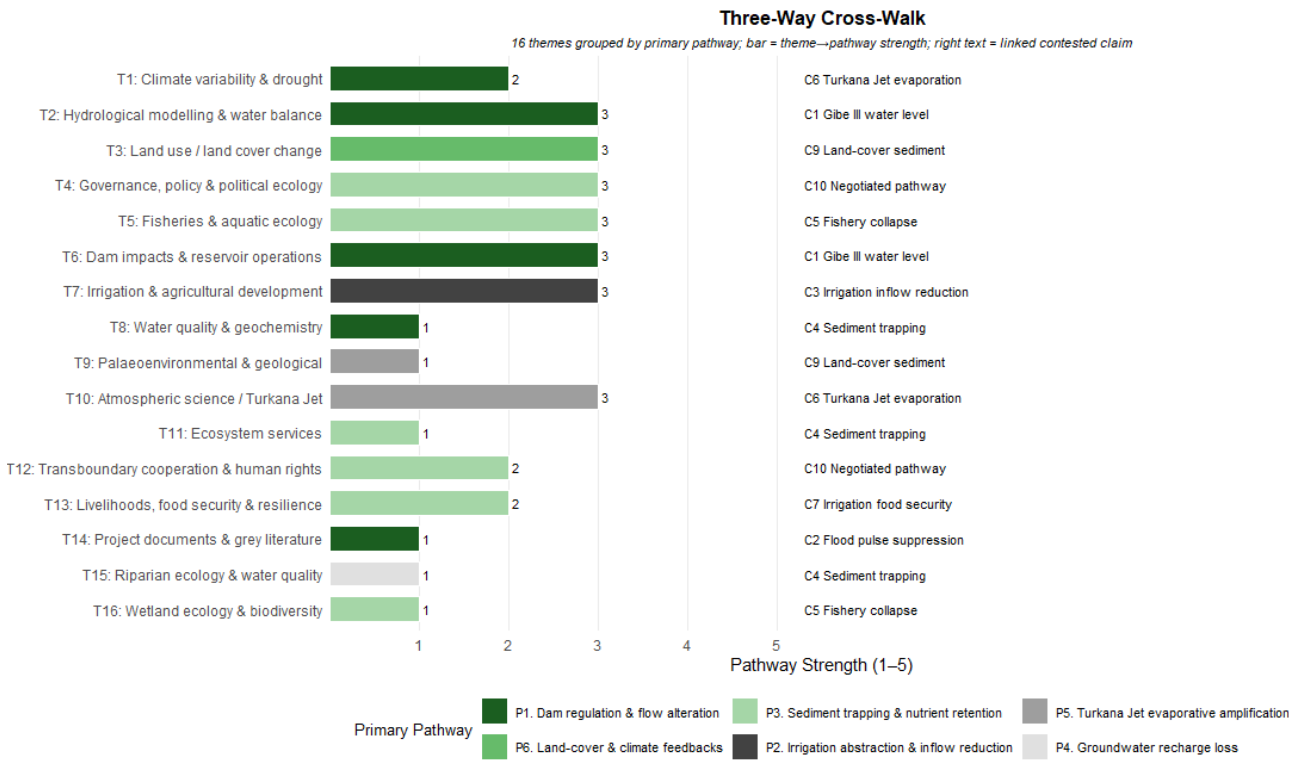

Figure 16. Three-way cross-walk linking each of the 16 thematic categories to its primary causal pathway and its primary contested claim, showing the theme to pathway strength on the five-point scale and the theme to claim link level.

4. Discussion and Conclusions

4.1 Sustainability of Ecological Functions under Flow Regulation and Climate Change

The first objective of this review (Section 1.9) was to determine whether the ecological functions of the Omo-Gibe Basin can be sustained under projected flow regulation and climate scenarios. The evidence assembled here converges on a negative answer for the current development trajectory and does so for a reason that is not primarily volumetric. Under regulation, dry-season flows rise from a natural 150-200 m³/s to approximately 490-525 m³/s, while wet-season peaks fall from 1,400-1,500 m³/s to approximately 640-700 m³/s; yet the regulated annual mean of about 569 m³/s sits only some 9% below the natural mean of 628 m³/s (Avery & Tebbs, 2018). The cascade therefore redistributes discharge far more than it removes it. Because ecological function in this system is carried by the seasonal pulse rather than by annual volume (Junk et al. 1989), that redistribution is itself the mechanism of loss, and any assessment framed on annual water balance alone will understate it.

Three quantified consequences follow from the loss of amplitude. First, seasonal lake-level oscillation explains 86% of the variation in the extent of the Aquatic-Terrestrial Transition Zone, so that compression of that oscillation from 1.0-1.5 m to approximately 0.3 m is projected to contract the ATTZ from a historical mean of 83.53 km² to approximately 21.3 km², a reduction of some 75% (Gownaris et al. 2017; Ethiopian Electric Power 2016a), although this projection is conditional on lake-level and shoreline conditions that predate the post-2019 expansion of the lake and remains unvalidated against it (Section 3.7). Second, primary productivity tracks Omo inflow directly: lake-wide chlorophyll-a fell by approximately 30% during the 2015-2016 filling of Gibe III, the peak-to-trough ratio compressed from 4.4 to approximately 2.0 under regulation, and abstraction scenarios project mean annual declines of 19% at 26% abstraction rising to 44% at 65% (Tebbs et al. 2020). Third, fisheries yield is governed by hydrological variables rather than by fishing effort (Kolding, 1992; Gownaris et al. 2017), and

compression of the natural intra-annual oscillation of 1.0-1.5 m to the projected regulated amplitude of approximately 0.3 m is projected to reduce yield by more than two-thirds, reflecting the modelled compression rather than a complete loss of intra-annual variation. The third of these carries a management implication that the other two do not: because the driver is hydrological, conventional fisheries instruments such as effort controls or gear restrictions cannot substitute for restoration of the flow regime.

Climate change compounds this trajectory, but with an important asymmetry in confidence. Projections agree on warming and on rising evapotranspiration, with an increase of approximately 21% by the 2080s under SSP5-8.5, yet they diverge sharply on precipitation, from a 24% decline (Lukas et al. 2025) to a 21.1% increase (Gebremichael et al. 2024). The evaporative side of the water balance is therefore better constrained than the supply side. Under the drying trajectory, geochemical buffering becomes the binding threshold rather than fisheries or productivity: Lake Turkana already sits at the mollusc extinction limit at pH 9.2 and total dissolved solids of approximately 2,500 ppm, held there by cation exchange on smectite clays that removes over 40% of incoming sodium (Yuretich & Cerling, 1983). Sustaining that buffering requires annual inflow in the order of 10 km^3, whereas abstraction approaching 54% of flow would drive continuous recession with no equilibrium (Avery & Tebbs, 2018). The answer to the first objective is therefore conditional rather than absolute. Ecological functions cannot be sustained under current provisions. Of the multiple controls on those functions, seasonal amplitude and minimum annual inflow are the two most directly amenable to operational decisions, and both remain hydrologically achievable. Delivering them, however, depends less on hydrology than on institutional capacity, since no basin-level authority is currently empowered to impose the required concessions (Section 4.3).

A further qualification concerns the framing of these findings. The evidence base, and this review with it, assesses change principally as loss relative to the pre-dam baseline, rather than as transition towards a new equilibrium under the regulated regime. The regulated flow regime will establish a different ecological state rather than simply a diminished version of the former one, and that state will require time to stabilize, with some functions reorganizing around the raised and more constant dry-season flows even as flood-dependent functions contract. Neither the timescale of that adjustment nor its endpoint can be established from the present evidence, since no empirical ecological monitoring study was identified after 2017 (Section 4.5); any account of the system's current trajectory would therefore be inference rather than observation. Resolving this is a further argument for resuming ecological monitoring, and it also bears on how environmental flow targets are set, since targets calibrated solely against the pre-dam baseline may not correspond to the state the system is now moving towards.

4.2 Minimum Environmental Flow Specifications

The second objective was to establish what the evidence base can and cannot support in specifying minimum environmental flows for the lower Omo and Lake Turkana. Existing provisions consist of a 10-day artificial flood release, and a continuous minimum flow of 25 m^3/s. Three observations follow. First, no ecological justification for either figure was identified in the Gibe III ESMP (Ethiopian Electric Power Corporation 2009b) or the Koysha ESIA (Ethiopian Electric Power 2016b). Second, the ten-day release is an order of magnitude shorter than the three-to-four-month inundation that sustained floodplain and recession processes (Section 1.2), and this duration mismatch is the one respect in which inadequacy can be established without reliance on contested models. Third, the artificial flood was not reliably delivered in the years immediately following reservoir filling (Hodbod et al. 2019), and no published assessment of delivery since has been identified, so current compliance is unknown rather than demonstrated. Whether the provisions are adequate in magnitude cannot be resolved on the present evidence, since the relevant thresholds derive from modelled and remotely sensed studies that remain unvalidated against post-2019 lake conditions (Section 3.7).

Read against the ecological functions identified in Section 1.5, the evidence base supports five minimum flow components, each tied to a distinct function and threshold:

1. A seasonal peak pulse exceeding 1,000 m^3/s sustained for three to four months, matching the June-September spawning window of migratory species and the natural chlorophyll-a bloom (Gownaris et al. 2017; Tebbs et al. 2020).
2. Seasonal lake-level fluctuation of at least 0.5-1.0 m, which would retain an estimated 30-40% of the original ATTZ; below approximately 0.3 m the zone becomes ecologically static (Gownaris et al. 2017).
3. Predictable overbank flooding of at least 30-60 days to support flood-recession cultivation, against which a 10-day release is short by an order of magnitude (Hodbod et al. 2019; Gebeyehu & Abbink, 2022).
4. A dry-season minimum of at least 50 m^3/s, double the current provision, to dilute reservoir-derived nutrient loads and limit conductivity in the delta and Ferguson's Gulf (Avery & Tebbs, 2018; Gibe III ESIA, 2009).
5. Annual inflow of at least 10 km^3, representing 50-60% of the natural average, to maintain the geochemical buffering that holds the lake below its salinity threshold (Yuretich & Cerling, 1983).

The gap between these specifications and current operations is one of incentive rather than hydrology. Extending the artificial flood from 10 to 30 days would restore approximately 60% of pre-dam chlorophyll-a, against approximately 20% under the present provision (Tebbs et al. 2020), while the opportunity cost of releasing the flood at all is estimated at US$7-11 million per year in foregone generation (SOGREAH Consultants, 2010). This is equivalent to roughly 2-9% of Ethiopia's recent annual electricity export revenue (US$118-339 million reported for FY2024/25) and a smaller fraction of Ethiopian Electric Power's total revenue (~US$773 million reported for FY2025/26), providing context for the scale of resistance such a cost might encounter from the utility. The same asymmetry appears in the filling record: prioritizing downstream preservation during the filling of Gibe III would have halved the resulting lake-level drop at a cost of 9% of hydropower generation, whereas the fast-filling approach actually adopted secured a 30.9% generation gain and produced the full 2 m decline (Zaniolo et al. 2021). This comparison is a modelled counterfactual analysis (Zaniolo et al. 2021): only the fast-filling approach was actually implemented, and its 2 m decline is consistent with observed reporting, whereas the alternative slower-filling scenario and its associated 9% generation cost are simulated outcomes, not an approach that was actually tested. Modest hydrological concessions therefore purchase disproportionate ecological returns, and the binding constraint on delivering them is the absence of any institution empowered to impose the concession. Given the divergence in precipitation projections noted above, these specifications should be adopted as adaptive targets governed by monitoring triggers rather than as fixed values pinned to a single historical baseline.

Findings of previous studies require further enhancement by revising modelled flow thresholds with field-verified indicators—actual fish spawning, floodplain recession agriculture, and Turkana inflow needs—gathered through community and pastoralist observation, combined with basin-wide stakeholder negotiation (dam operators, irrigators, downstream communities) to jointly recalibrate seasonal amplitude and minimum-inflow targets against lived, seasonal ecological and livelihood evidence. Considering the Omo Gibe basin has been poorly monitored in the past, future studies can build on new river flow data being generated by the Ministry of Water and Energy of Ethiopia.

4.3 Impact Pathways, Ecosystem Services and Governance Constraints

The third objective was to produce a coherent framework capturing the interconnected character of the impact pathways, the multi-dimensional structure of ecosystem service flows, and the governance constraints that amplify ecological risk. The causal pathway network (Figure 11) delivers the first of these, and its most consequential structural feature is the position of the convergence nodes. Lake-level decline and fishery decline receive multiple pathways, and livelihood loss and food insecurity sit downstream of fishery decline rather than alongside it. Both fishery decline and food insecurity are best understood as convergence points for modelled pathway effects rather than as independently confirmed causal outcomes. Social endpoints in this basin are therefore consequences of ecological ones, which means that interventions targeting livelihoods directly cannot substitute for interventions targeting the upstream hydrological drivers. This ordering is the single most policy-relevant output of the pathway analysis.

The pathways also compound. Flow regulation reduces the volume of freshwater available to dilute and buffer the effects of irrigation abstraction downstream available to buffer irrigation abstraction (P1 × P2); sediment starvation reduces nutrient supply while the Turkana Jet sustains high evaporative demand (P3 × P5); and groundwater depletion erodes baseflow resilience precisely as climate variability increases (P4 × P6). Because these interactions are multiplicative rather than additive, single-pathway mitigation, of which the 10-day flood is the clearest example, will under-perform against expectations derived from any one pathway in isolation. No coupled model of the six pathways yet exists, so the magnitude of that under-performance cannot presently be quantified. The theme-pathway matrix (Figure 11) shows where the framework rests on firm ground and where it does not: of 96 theme-pathway cells, 18 are well-covered, 58 under-covered and 20 are gaps, with the gaps concentrated on the groundwater (P4) and atmospheric (P5) limbs.

On the ecosystem service dimension, the losses documented in Section 1.7 are not distributed evenly across service categories but are concentrated where substitution is least available. Provisioning services have absorbed the sharpest change: approximately 200,000 people depend on Lake Turkana fisheries and approximately 90,000 depended on flood-recession agriculture, and roughly 95% of Nyangatom households now report chronic food insecurity following the loss of the recession system (Gownaris et al. 2017; Hodbod et al. 2019; Gebeyehu & Abbink, 2022). Because pastoralists who lose livestock have historically turned to fishing as a fallback, these two systems functioned as sequential rather than independent safety nets, and both have been undermined by the same driver. Regulating services have not simply been diminished but altered in character. Water, Peace and Security (2024) describe a flooding paradox in which localized water shortages below the reservoirs coexist with damaging flooding further downstream, a pattern also noted in the BRIGHT baseline assessments (Water and Land Resource Centre 2024d). As set out in Section 1.7, this reflects the interaction of reservoir release schedules with seasonal variability, intervening land and water use, and lake hydrodynamics rather than reservoir operations alone. Its ecological significance is that inundation occurring outside the historical flood window is unlikely to perform the floodplain-fertility and recharge functions of the natural pulse, though the groundwater component of this remains unquantified (Section 3.4). These are distinct effects operating in different zones: lost

fertility and recharge from mistimed inundation are floodplain effects, whereas altered inflow timing affecting the Aquatic-Terrestrial Transition Zone and lake productivity are lake-area effects.

In the Omo-Gibe basin, future studies need to integrate water quality in ecosystem services studies. This integration can link specific water quality parameters to specific services; pair water-quality sampling with flow-threshold studies; and use participatory, low-cost water quality monitoring. This ensures ecosystem service assessments reflect both water quantity and quality.

The governance dimension explains why the ecological and service losses have proceeded without correction. The Omo-Gibe Basin retains the highest groundwater recharge rate among Ethiopia's major basins and uses an estimated 4% of available supply, yet records piped water access of 45.9% and ranks second worst of the five BRIGHT basins on food insecurity (Water and Land Resource Centre 2024b, 2024d). The binding constraint is institutional, not physical. No Basin Administration Office has been established under either Proclamation 534/2007 or its 2025 successor, so Proclamation 1375/2025 confers the strongest integrated water resources management mandate in Ethiopian history on a political-level Council that has no implementation arm at basin scale. The consequences compound one another: without monitoring stations there is no data, without data there is no evidentiary basis for permits or basin plans, and without a Basin Administration Office there is no institution to collect, manage or act on either. At the transboundary scale the void is equally complete, and it persists despite an economic case that points the other way, with cooperative management projected to yield a benefit-cost ratio of 16.7 against 5.0 under non-cooperative full irrigation, and non-cooperative trajectories capable of depleting the lake within 15.5 years (Englezos et al. 2023).

4.4 SDG Alignment and Trade-offs

The fourth analytical component examined synergies and trade-offs across the nine SDGs retained by the screening in Section 2.10. The alignment matrix (Figure 13) exposes a systematic mismatch between where risk is concentrated and where evidence is concentrated. The strongest alignments are between hydrological modelling and SDG 6, and between governance and SDG 16, while SDG 14 and SDG 2, which the substantive evidence identifies as the goals most empirically at risk in the basin, are carried by themes flagged as sparse in the evidence density assessment (Figure 8). SDG 7 presents the inverse problem: the gains are real and nationally significant, but the evidence base supporting them is narrow, resting almost entirely on dam-impacts and reservoir-operations literature, and it excludes hydropower's own climate vulnerability, projected at a 10.5-14.8% reduction in Koysha generation by the 2060s (Hailu et al. 2025). Evidence-building for SDG 16 warrants particular priority, because the governance cluster is small relative to the magnitude of the trade-offs it is expected to mediate.

The structure of the trade-offs is itself counter-intuitive and consequential for how the basin is managed. Multi-objective optimization identifies the sharpest conflict as running between irrigation supply and fish production ($r = -0.85$), followed by irrigation and the Lake Turkana ecosystem ($r = -0.80$) and hydropower and sediment transport ($r = -0.70$), while hydropower and irrigation are mildly synergistic ($r = +0.30$) (Giuliani et al. 2022). The cascade is therefore well designed for the two upstream objectives simultaneously, and the costs of that design fall almost entirely on downstream ecological and social endpoints. These correlations are themselves derived from a multi-objective optimization model (Giuliani et al. 2022) subject to the same flow-regulation, inundation-period and amplitude-variability uncertainties flagged elsewhere in this review, so the trade-off structure should be read as indicative rather than a settled conclusion. The trade-off is not, as public and policy debate often frames it, between energy and agriculture; it is between both of them together and the downstream floodplain-to-lake system.

4.5 Confidence, Limitations and Research Priorities

The conclusions above must be read against the limits of the evidence supporting them. No quantitative claim about this basin is uncontested: every one of the ten claims examined attracts at least one contradicting or ambiguous document (Figure 14). More significantly, the two claims rated Unresolved, C3 (irrigation abstraction permanently reduces lake inflow) and C7 (irrigation expansion increases household food security), are precisely those for which irrigation is the upstream driver. This is consistent with the cross-walk finding that P2 is anchored by only one theme, T7 (Figure 15). The irrigation limb is therefore the weakest element of the causal architecture, and it is also the limb on which the largest outstanding abstraction decisions depend. Confidence in dam-driven mechanisms is considerably higher than confidence in irrigation-driven ones, and this asymmetry should be made explicit whenever the synthesis is used to support decisions about the Kuraz scheme.

Five further limitations qualify the synthesis. The hydrometric network carries a 57% station deficit, seven sub-basins have no monitoring infrastructure at all, and post-2005 discharge records remain inaccessible, so that much of the hydrological evidence rests on modelled rather than observed values (Haile et al. 2022; Water and Land Resource Centre 2024b). No empirical ecological monitoring study, as distinct from model projection, was identified after 2017, which means the headline projections of a 67-72% fisheries decline and a 75% ATTZ contraction remain empirically unvalidated in the post-Gibe III operational era. Research effort is geographically

skewed towards the Kenyan side of Lake Turkana, leaving the Omo delta and the Ethiopian shore comparatively unstudied (Obiero et al. 2023). The evidence base is also less independent than the document counts imply: several of the most frequently cited sources share authorship, most notably Hodbod et al. (2019), which is a consensus synthesis produced by expert elicitation among a research network whose members are also lead authors of other documents cited separately throughout this review. Where such documents are counted as convergent under the criteria set out in Sections 2.6 and 2.11, the resulting confidence ratings may overstate the degree of independent corroboration. Finally, thematic categorization and the quality appraisal were performed by a single reviewer, so borderline assignments rest on individual judgement.

Eight research priorities follow directly, and each addresses a gap identified in the analysis rather than a general call for more data. Four concern observational foundations:

- **Re-establishing the hydrometric network**, aligned with the recent MoWE initiative and with particular attention to the seven unmonitored sub-basins, since every other priority depends on it.
- **Paired surface-water and groundwater monitoring** around Lake Turkana and in the lower Omo Valley, to quantify lake–groundwater exchange and test whether the subsurface buffer is contracting.
- **Atmospheric monitoring of the Turkana Jet**, to integrate jet-driven evaporation into basin water-balance models from which it is currently absent.
- **Resumption of empirical ecological monitoring**, to ground-truth the projections on which management currently relies.

Four concern analysis and scope:

- **Formal attribution of historical lake-level change**, separating the contributions of dam filling and operation from rainfall variability, land-use intensification, evaporative demand and possible groundwater or tectonic influences. Recent evidence indicates that non-dam drivers can dominate at regional scale (Byrne et al. 2024), yet no study partitions them for Lake Turkana, leaving the basin's most policy-salient claim unresolved.
- **Measurement of actual as distinct from designed irrigation abstraction** in the lower Omo, including conveyance losses and return flows. This is the weakest limb of the causal architecture and the one on which the largest outstanding decisions depend.
- **Coupled-system modelling of the six pathways**, to quantify the compound effects that single-pathway assessment cannot capture.
- **Integration of water quality into ecosystem service and environmental flow assessment**, linking specific water-quality parameters to specific services and pairing water-quality sampling with flow-threshold studies, so that provisions reflect both the quantity and the quality of delivered water.

Together these would convert a model-based evidence base into an observation-based one capable of supporting adaptive management, and would resolve the attribution and abstraction questions on which basin-scale and transboundary decisions now depend.

4.6 Conclusions

Seven conclusions follow from the review.

1. The basin's endorheic character means that upstream interventions are transmitted to Lake Turkana without the dilution or downstream buffering available in exoreic systems, although the lake's own geochemical buffering and the inputs of the intervening catchment moderate this transmission. The system cannot be assessed as a series of independent projects, and a cumulative Strategic Environmental Assessment remains the outstanding requirement.
2. The seasonal flood pulse is a central variable linking hydrological, ecological and livelihood function in this system. Its alteration, rather than any reduction in annual volume, is a principal mechanism through which basin transformation propagates, and this distinction should inform how future interventions are assessed.
3. Current environmental flow provisions appear insufficient by orders of magnitude, most clearly in duration: a 10-day artificial flood cannot substitute for the three-to-four-month inundation on which floodplain and recession processes depended. The available evidence points towards a sustained seasonal peak pulse, predictable overbank flooding of at least 30–60 days, a seasonal lake-level fluctuation in the range of 0.5–1.0 m, a dry-season minimum of at least 50 m^3/s, and annual inflow in the order of 10 km^3 as indicative starting specifications. These values are derived predominantly from modelled and remotely sensed studies, are drawn from a hydrological record with a 57% station deficit,

and have not been tested against field observation or stakeholder deliberation. They should therefore be treated as hypotheses for validation rather than as prescriptive thresholds, and the immediate priority is field-based, stakeholder-engaged research — combining ecological verification with negotiation among dam operators, irrigators and downstream communities — to develop adaptive flow provisions for the basin.

4. The scenario analysis (Section 3.5) and the multi-objective optimization results (Section 4.4) both indicate that the sharpest trade-off runs between irrigation supply and lake fisheries, not between hydropower and irrigation. The cascade is well optimized for both upstream objectives simultaneously, and the resulting costs fall disproportionately on downstream ecological and social endpoints in both Ethiopia and Kenya.

5. Governance, rather than physical water scarcity, appears to be the binding constraint. Of the ten contested claims examined, the least contested was that a negotiated management pathway outperforms full irrigation expansion (Section 3.7), yet the governance and transboundary evidence base is among the thinnest in the review and is only weakly connected to the hydrological themes it would need to act upon (Sections 3.3, 3.4 and 3.6). This institutional deficit is compounded by the continued absence of a Basin Administration Office, leaving the integrated water resources management mandate conferred by Proclamation 1375/2025 without an implementation arm at basin scale.

6. Confidence is unevenly distributed across the evidence base. Dam-driven mechanisms are well supported, whereas the groundwater and atmospheric limbs remain weakly evidenced and the two irrigation-driven claims are unresolved, which is consequential given that the largest outstanding abstraction decisions concern irrigation.

7. Monitoring is a precondition for adaptive management rather than a by-product of it. Until the hydrometric network is rebuilt and empirical ecological monitoring resumes, the basin's central projections cannot be validated, and management will continue to rely on modelled values that observational records suggest diverge from actual conditions.

Taken together, these conclusions point to a single shift: from project-level mitigation towards basin-wide, ecologically informed and adaptive environmental flow management. The foundations for that shift are largely in place, in the 2024 Basin Plan, the BRIGHT Project's institutional-support program, and the 2025 statutory reforms. What is absent is the institutional capacity to convert them into operational protection at the pace at which the hydrological transformation is proceeding. Koysha is expected to become operational before most of the monitoring and institutional measures identified here could be delivered, which makes the sequencing of reform, rather than its content, the immediate constraint.

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