Pressure-State-Response (PSR) Framework for Wetland Assessment - a note from Lake Tana Biosphere Reserve (LTBR) UNESCO World Heritage site (Ethiopia)

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Abstract:

Wetlands in the Lake Tana Biosphere Reserve (LTBR) provide essential ecosystem services but face rapid degradation driven by anthropogenic pressures and climate variability. We operationalize a Pressure–State–Response (PSR) framework by integrating multi-temporal remote sensing with participatory citizen science linking spatial evidence to locally grounded insights. Landsat and Sentinel-2 (2011–2025) support land-cover and fragmentation analysis; participatory mapping, focus groups, and expert interviews validate and contextualize spatial trends. Our results show strong correlations between high population density, cropland expansion from 78% to 85% (2011–2025), and deteriorating ecological state, with pronounced impacts in eastern floodplains. The integrated approach offers actionable evidence for targeted, adaptive wetland management in LTBR and similar systems.

Keywords: *Lake Tana Biosphere Reserve, PSR Framework, Remote Sensing, Citizen Science, Wetland Degradation, Landscape Metrics*

1. Introduction

Wetlands are among the most biologically diverse and valuable ecosystems in the biosphere, serving as natural water purification systems, facilitating groundwater recharge, and providing critical flood control mechanisms (Guo et al., 2017). Beyond these regulatory services, they act as vital habitats for endangered flora and fauna and offer significant socio-economic benefits to human populations globally. However, despite their recognized importance, wetlands are undergoing rapid degradation worldwide (Mohammed & Mengist, 2018).

In 2015, the Lake Tana Biosphere Reserve (LTBR) was designated encompassing Ethiopias largest fresh water body. These wetlands are foundational to the region's hydrology, fisheries, and shoreline protection (Erwin et al., 2009; Junk et al., 2013).

Despite their international and local significance, the wetlands of the LTBR face persistent and growing threats. Biological invasions (notably water hyacinth), heavy sedimentation, and widespread land-use changes have significantly altered their state (Mohammed & Mengist, 2018; Stave et al., 2017). A critical driver of this degradation is the socio-cultural misconception of wetlands as unproductive "wastelands," leading to systematic drainage for agricultural expansion.

Current management frameworks often fail to bridge the gap between high-level policy and grounded ecological realities. To address this, the "ComWet" project (https://africa-uninet.at/en/projects/call4/p144-ethiopia) funded by Africa UniNet, is being established to develop a participatory, problem-oriented wetland health assessment approach.

Central to the ComWet project is the integration of "Citizen Science" with advanced geospatial technology. In this study, we propose and apply an adapted Pressure-State-Response (PSR) framework—derived from the European Environmental Agency's DPSIR model—to assess the health of the LTBR wetlands (Kristensen, 2004). The PSR framework is uniquely suited for this context as it explicitly links socio-economic drivers (Pressures) to ecological changes (State) and management actions (Response), providing a clear cause-and-effect narrative (chain). By synthesizing multi-temporal remote sensing with participatory data, this study seeks to identify suitable indicators for environmental monitoring and provide efficient evidence to support LTBR management programs and inform long-term ecological monitoring strategies.

2. Methods

2.1.The Study Area

The Lake Tana Biosphere Reserve is located in the Amhara National Regional State (Fig. 1), in the northwestern part of Ethiopia, between 11°25'07"N - 12°29'18"N and 36°54'01"E - 37°47'20" E. It covers a total surface area of 695,885 ha of which the Core area(s) consist of 22,841 ha (terrestrial: 7,699 ha), Buffer area(s): 187,567 ha (terrestrial: 30,969 ha), and Transition area(s): 485,477 ha (terrestrial: 354,297 ha).

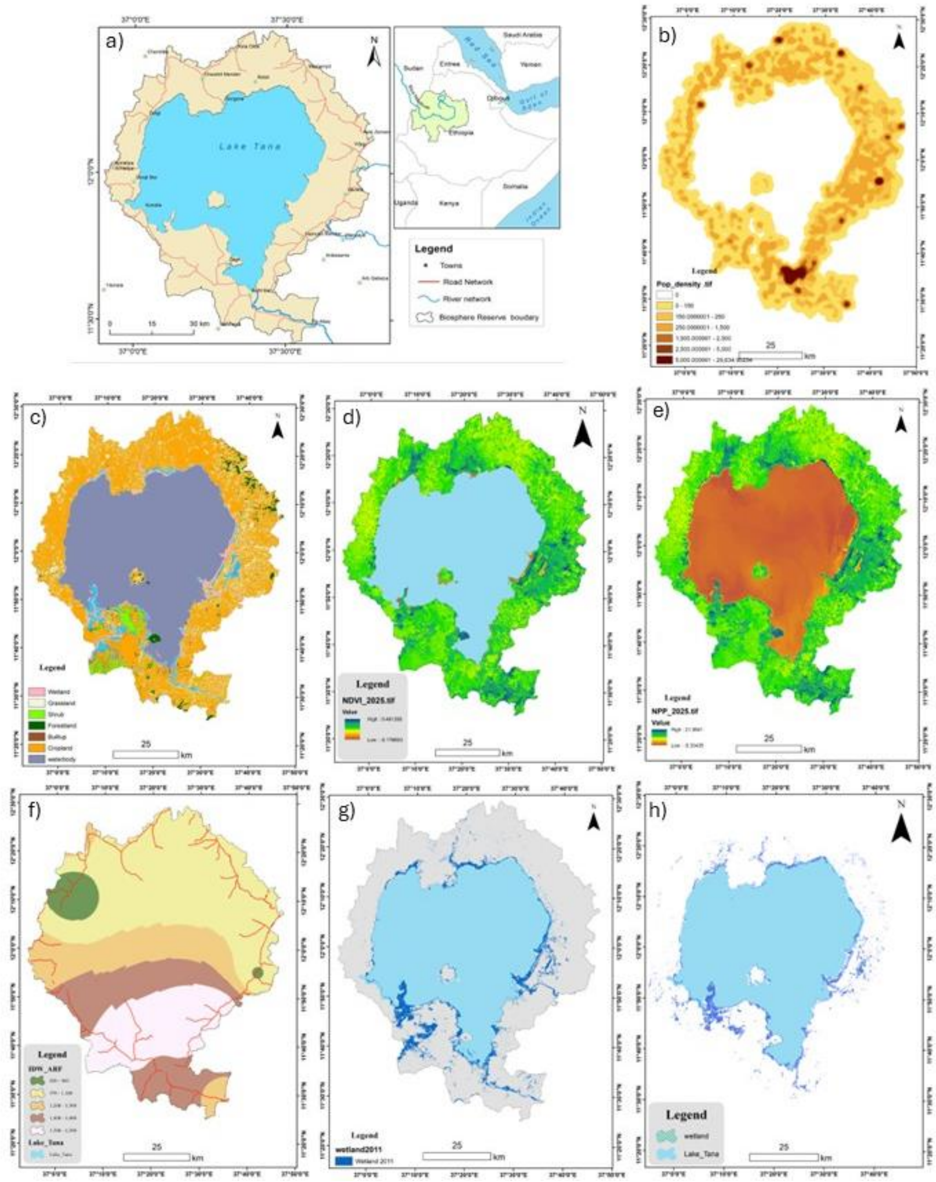

Figure 1: a) Study area, b) population density, c) land use and land cover, d) Normalized Difference Vegetation Index (NDVI), e) Net Primary Productivity (NPP), annua rainfall distribution (f), wetland distribution derived from the Landsat imagery in g) 2011and h) in 2025.

2.2.Conceptual Framework

The research is grounded in the Pressure-State-Response (PSR) model (Rapport, 1979), which serves as the core analytical framework (Fig.2). This model is operationalized through two primary, complementary methodological pillars: remote sensing (RS) and participatory citizen science (Fraisl et al., 2022). This tripartite approach ensures a comprehensive analysis that combines spatio-temporal data with grounded local and institutional knowledge.

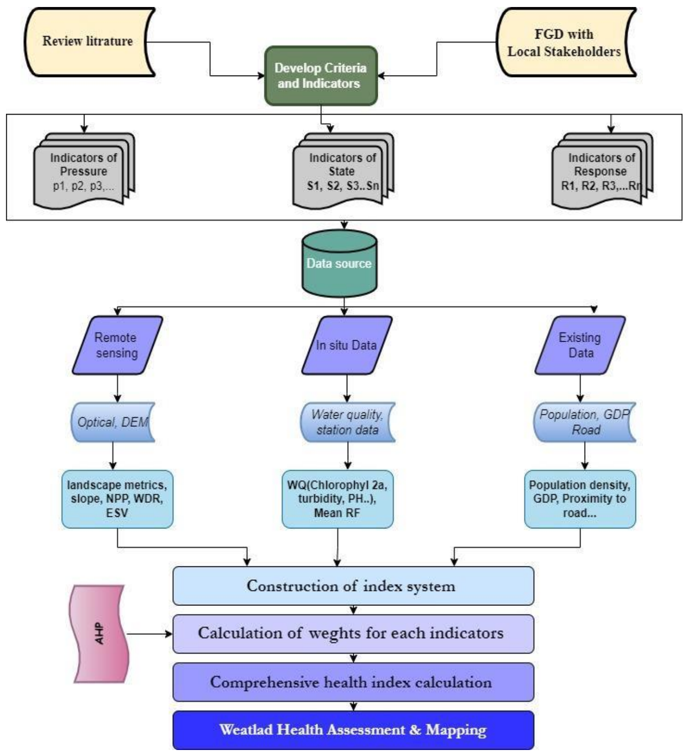

Figure 2: The Pressure-State-Response (PSR) methodological framework for the health assessment of wetlands in the Lake Tana Biosphere Reserve (source: ComWet project).

2.3. Dataset type and sources

We compiled socio-economic and infrastructure datasets alongside multi-temporal satellite imagery (Landsat/Sentinel-2) to derive core landscape metrics for assessing wetland pressures and state.

2.4. Data Analysis

2.4.1. Remote Sensing and Spatio-Temporal Analysis

To quantitatively assess the State and Pressures within the PSR model before and after the LTBR designation, a time-series analysis across three periods: pre-2015 (baseline), post-2015, and 2025 was conducted. All images are pre-processed (radiometric calibration, atmospheric correction, registration) to ensure consistency. Techniques including supervised classification, spectral indices (e.g., NDVI), and LULC change analysis are employed to identify patterns of wetland loss, fragmentation, and hydrological alteration, with GPS-based field observations used to ground-truth and validate the results.

2.4.2. Participatory Citizen Science and Community Engagement

To contextualize the remote sensing data and investigate the Drivers, Pressures, Impacts, and Responses within the DPSIR model, a community-based citizen science approach is adopted, integrating local and institutional knowledge into the scientific process (Fraisl et al., 2022). This is achieved through Focus Group Discussions (FGDs) with community representatives to capture local perceptions and socio-economic insights, participatory community mapping to delineate boundaries and identify degradation hotspots, and semi-structured interviews with experts and local knowledge holders to incorporate technical and managerial perspectives.

3. Results & Discussion

This study systematically identified and computed a set of indicator variables to capture the complex interactions between human pressures, ecological states, and management responses, and their impact on wetland health. This approach enables us to pinpoint the wetland status of LTBR and develop targeted conservation strategies.

Pressure indicators:

In the causal chain of the DPSIR framework in this study, pressure indicators represent the driving factors and human activities practiced to meet the growing demand theory excerpt pressures on the environment (Kristensen, 2004). Pressure indicators can be categorized into three types: a) excessive use of environmental resource, b) change in landuse or c) emission to the water or air. The identified indicators in the LTBR contribute directly or indirectly to all of them.

Population density contributes to excessive resource use and increased emissions, while its spatial pattern serves as a proxy for the intensity of human pressure. Densely populated areas reflect intensive human activity, where wetlands are particularly vulnerable to conversion into agricultural land, settlements, and infrastructure like roads (Fig. 1 b, c). Previous studies show that recession agriculture and settlement expansion are common practices that accelerate wetland degradation (Fetaw et al., 2022; Gebremedhin et al., 2018; Stave et al., 2017). These trends are also supported by citizen monitoring and local community involvement. More broadly, wetland conversion to agriculture is a major global driver of biodiversity loss and ecosystem degradation (Ramsar Convention Secretariat, 2018), and the Lake Tana Biosphere Reserve (LTBR) reflects this broader pattern. Together, population growth, cultivated land expansion, infrastructure development (roads), and urbanization illustrate how socio-economic development trajectories intersect with ecological vulnerability, intensifying stress on wetland systems.

State Indicators:

The state of the environment is the combination of the physical, chemical, and biological conditions (Kristensen, 2004; Gayen & Datta, 2023). Net Primary Productivity (NPP) is one that is a key measure of ecosystem function, reflecting vegetation vigor and biomass accumulation over time (Deb Burman, 2021; Wang et al., 2024). In this study, NPP was derived from NDVI, with values ranging from 0 to above 25 g/m^2. The majority of the LTBR exhibits low productivity (<5 g/m^2), while approximately 667 km^2 experience moderate productivity (10–20 g/m^2), and areas with high productivity (>20 g/m^2) are relatively insignificant (Fig.1 d, e). Localized zones of higher productivity correspond to intensified cultivation and settlement expansion, while widespread low values signal reduced vegetation resilience and potential wetland degradation.

Rainfall distribution is another state indicator, showing a mean annual range of 850–1500 mm. The southern districts, including Dera, Bahir Dar Zuria, Dangla, and Alefa, receive relatively higher rainfall, while much of the remaining reserve experiences annual totals below 1200 mm (Fig. 1 f). This uneven distribution sustains hydrological connectivity in wetter zones but also increases risks of flooding, sediment deposition, and nutrient loading. In the context of the PSR framework, rainfall acts as a natural driver and a pressure intensifier (Gayen & Datta, 2023).

Landscape fragmentation metrics indicate that wetlands are increasingly divided into smaller, isolated patches, reflecting a fragmented ecosystem state characterized by stronger edge effects, reduced habitat quality, and greater landscape heterogeneity due to expanding cropland and settlements. Water quality provides an additional indicator of degradation, as wetlands near cultivated and settled areas are increasingly affected by nutrient loading, turbidity, and pollution, which contribute to eutrophication and reduced macrophyte diversity.

Together, state indicators provide a comprehensive assessment of the ecological condition, illustrating how specific pressures such as population density, intensive cultivation, road infrastructure, and urbanization manifest as measurable shifts in ecosystem state.

Response indicators:

Response indicators reflect the manifested consequences of pressures and states, expressed as wetland degradation and the decline of ecosystem service values (Hazbavi, 2020; Kristensen, 2004). In the LTBR, wetlands are distributed unevenly, with the majority concentrated in the east, particularly on the Fogera floodplain (Fig. 1 g, h). This spatial pattern creates diverse ecological zones where pressures and states interact differently, shaping distinct trajectories of wetland health (BoEPLAU, 2015; Stave et al., 2017). Wetland degradation is not uniform but context-specific, driven by the interaction of climatic variability and human activity.

As wetlands fragment and lose ecological integrity, their capacity to provide ecosystem services will decline. The Lake Tana wetlands are critical for regulating water flow, supporting biodiversity, and sustaining fisheries, providing grazing land, and buffering floods. However, degradation will reduce these services, undermining both ecological sustainability and local livelihoods.

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