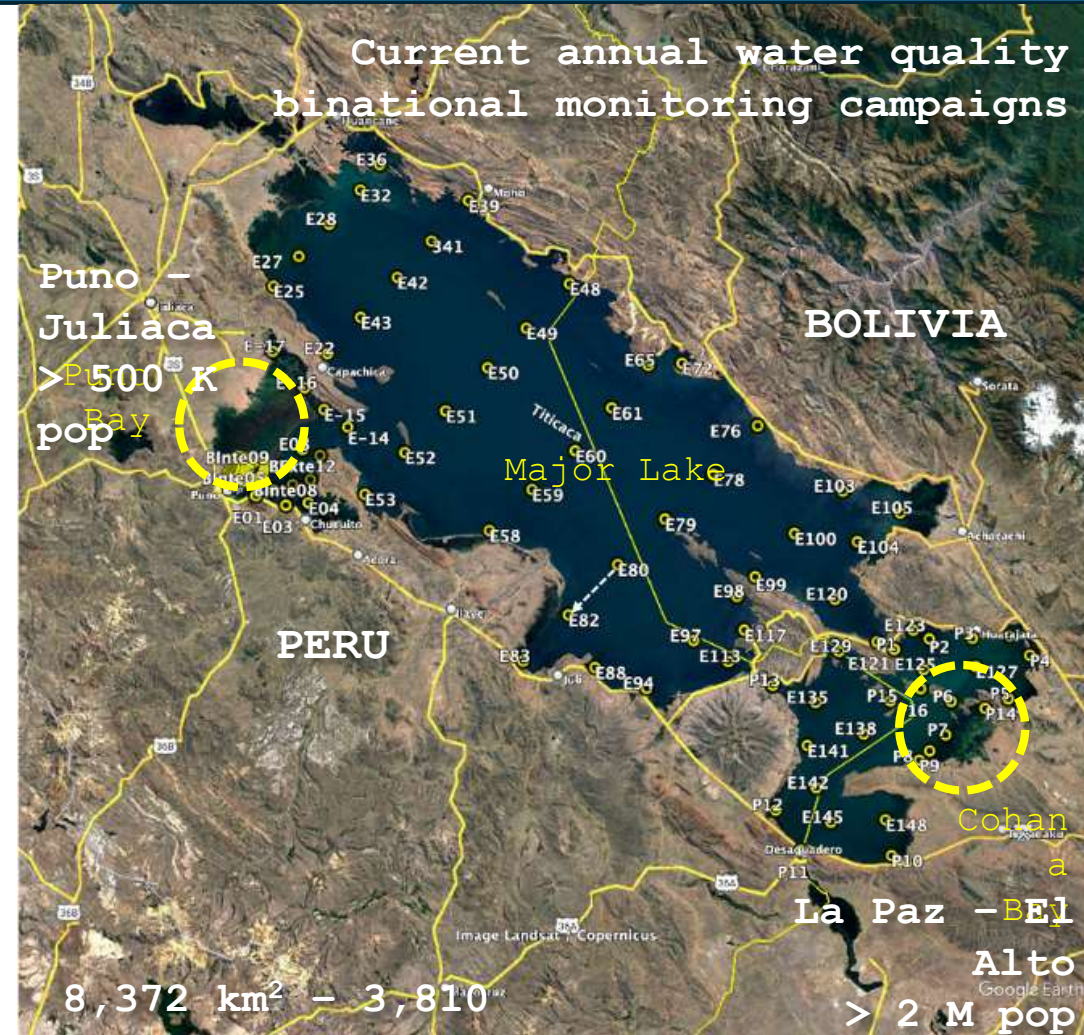


Limnological Monitoring of Lake Titicaca – Puno Bay Case Study

Trophic States (OCDE 1982) vs. Optical States (OWT 2017), Algal Blooms Early Warnings & Urgent Management Recommendations



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INBO World Basin Summit 17/06/2026 – Session 1 – DATA:

From data to action: modernizing water resources monitoring for resilient basin management



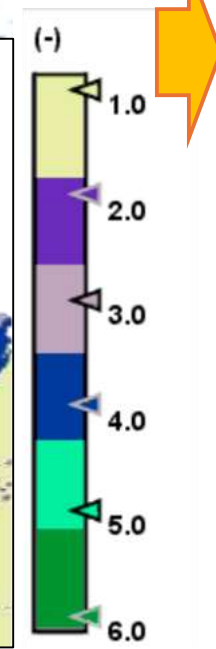
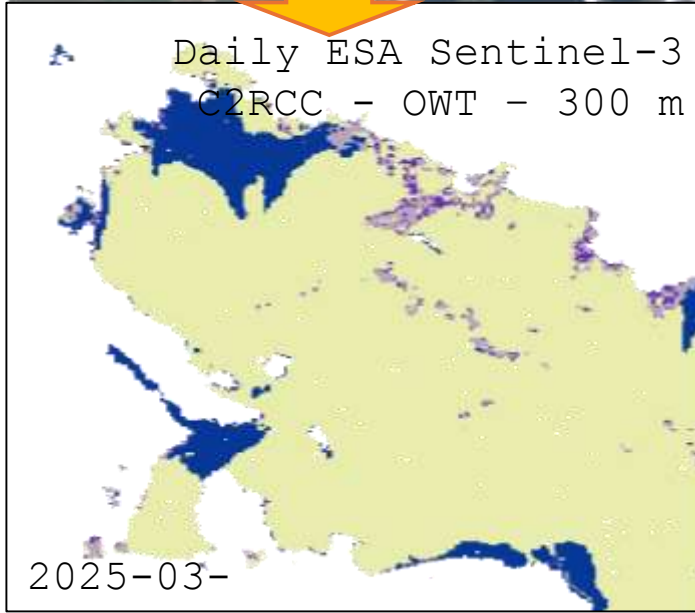
Current Limitations

Annual water quality binational monitoring campaigns (2014+)

- Spot sampling ~70 points, 2-week campaigns, 2 scientific boats, tens of specialists, >2 months data analysis and interpretation (reactive)
- **High costs: fossil fuel (diesel) + logistics**
- **Surface measurements 20-30 cm**
- Mostly pelagic zones, not shallow littoral
- **GOAL: permissible thresholds respected based on water quality standards (Peruvian ECA)**
- 20 physicochemical parameters + 2 coliforms + >21 trace metals: not major limnological variables
- **Ecological health not evaluable**
- **Impossible forecasts and early warnings**
- Management recommendations by parameter-bottom profiles (100 m)
- High frequency (1 Hz)
- Real-time
- Variables: Cond, Temp, ODO% CB, pH, ORP, Turb, Chl-a, Phycocyanin,

(2) Technological advances

using Satellite Remote Sensing



Lake responses to climate changes and human pressures?

Proposed innovative monitoring
In high frequency and real time

- Determine trophic states (OECD 1982) spatial distribution
- Discriminate zones using Cluster Analysis
- Identify key variables using PCA
- Determine optical water types (OWT 2017)
- Validate satellite Chlorophyll-a data using *in situ* data
- Locate eutrophication zones
- Generate Blooms early warnings
- Suggest protection and restoration measures

Contribute to public policies

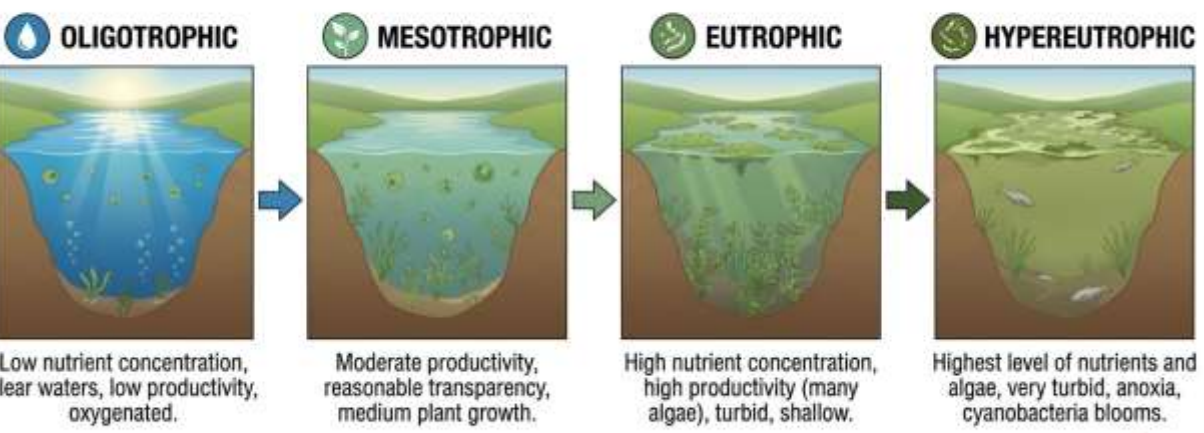
In Limnology, Trophic States = a scientific basis for understanding eutrophication processes (response to nutrient enrichment); a practical tool for management, monitoring, and regulation; an early indicator of environmental degradation (algal blooms).



OECD = Organisation for Economic Cooperation and Development

TROPHIC STATES OF A LAKE

Biological productivity based on nutrients (N and P)



Increase of Nutrients and Biological Productivity

OWT	Chl-a (µg/L) min-max	CDOM (g/m³) min-max	TSM (g/m³) min-max
1	0.1 - 12.3	0.04 - 1.03	0.15-14.70
2	0.8 - 69.6	0.9 - 20.43	0.87-52.28
3	1.3 - 33.0	0.05 - 8.0	0.28-208.9
4	0.9 - 705.0	0.27 - 18.67	1.70-190.07

C2RCC / SNAP:
 ophyll-a (µg/L)
 CDOM (g/m³)
 TSM (g/m³)

OECD (1982) Trophic State Classification Criteria

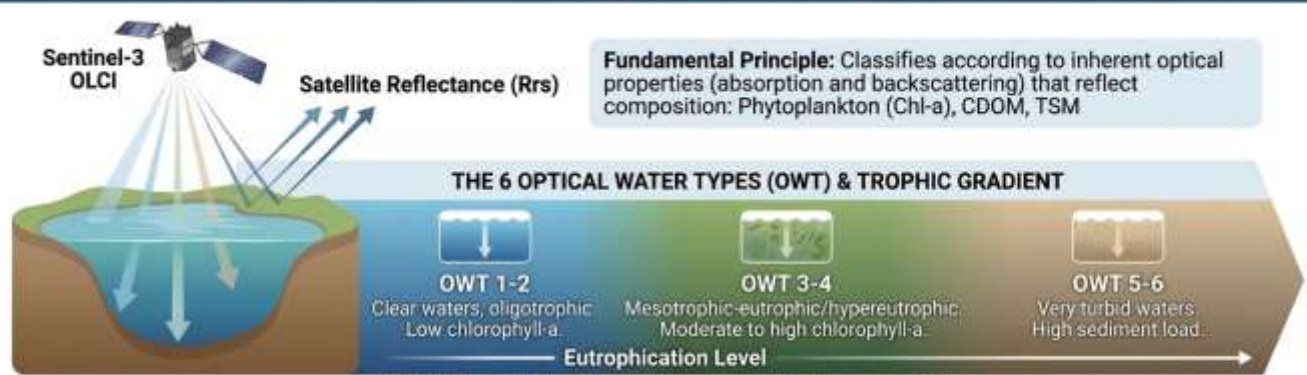
Source: OECD (1982)

Parameter (Unit)	→ INCREASING NUTRIENT LOADING / DECREASING CLARITY →			
	Oligotrophic	Mesotrophic	Eutrophic	Hyper-eutrophic
Total Phosphorus (µg P/L)	3.0 - 17.7	10.9 - 95.6	16.2 - 386	750 - 1200
Total Nitrogen (µg N/L)	307 - 1630	361 - 1387	393 - 6100	
Chlorophyll-a (µg Chl-a/L)	0.3 - 4.5	3.0 - 11	2.7 - 78 ²	100 - 150
Secchi depth (m)	5.4 - 28.3	1.5 - 8.1	0.8 - 7.0	0.4 - 0.5

*Values indicate range of OECD (1982) criteria.

Eleveld et al.

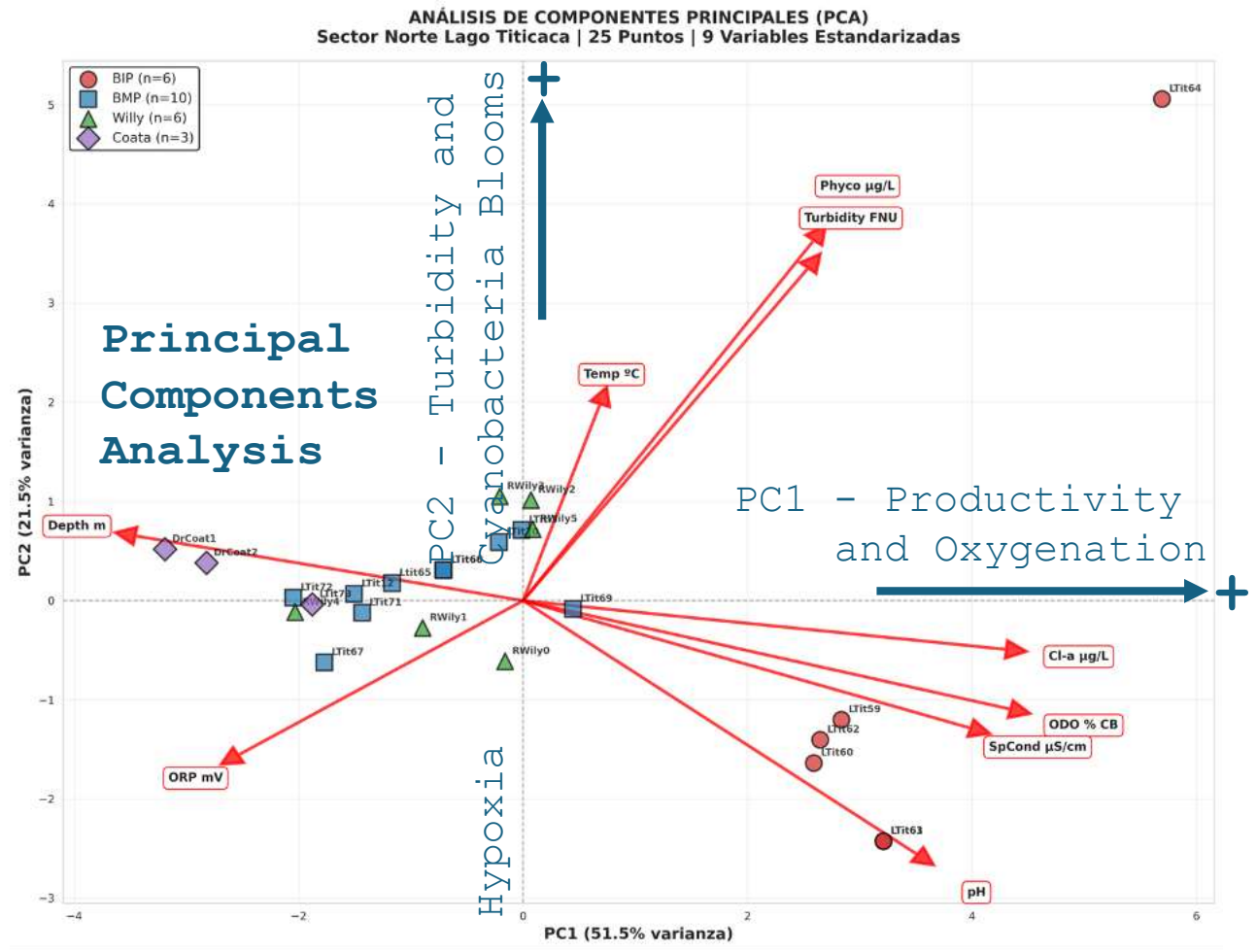
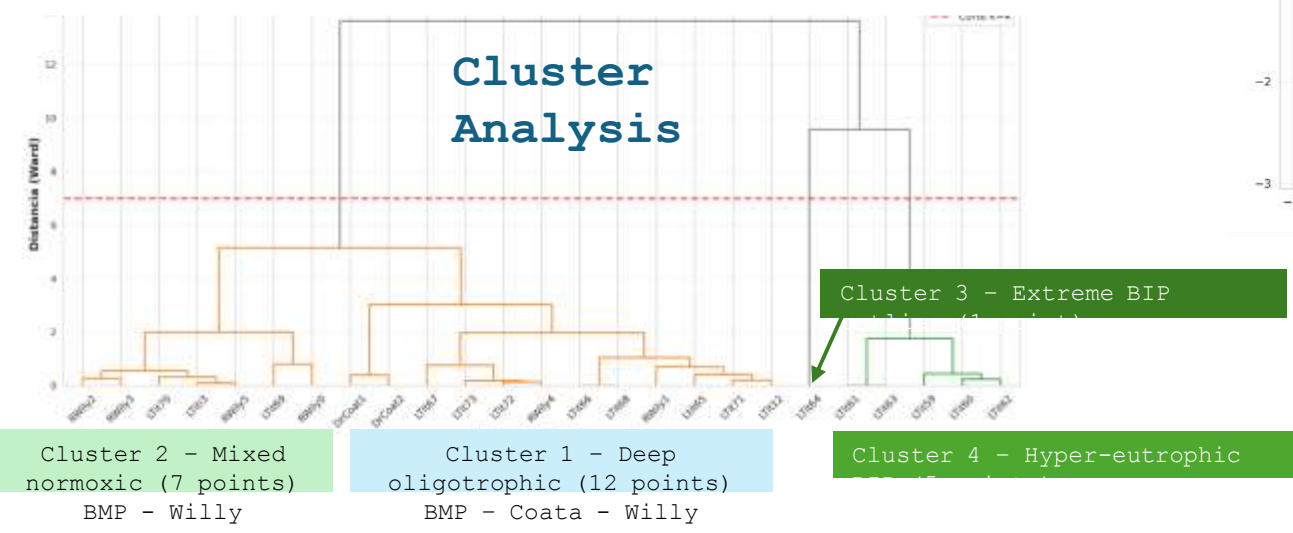
THE OWT CLASSIFICATION: OPTICAL WATER TYPOLOGY BY REMOTE SENSING



Note: High variability within each type; the median is representative.

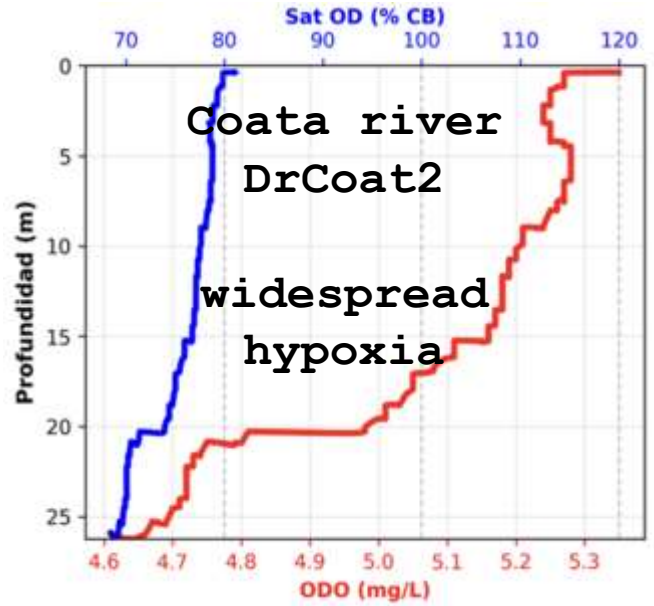
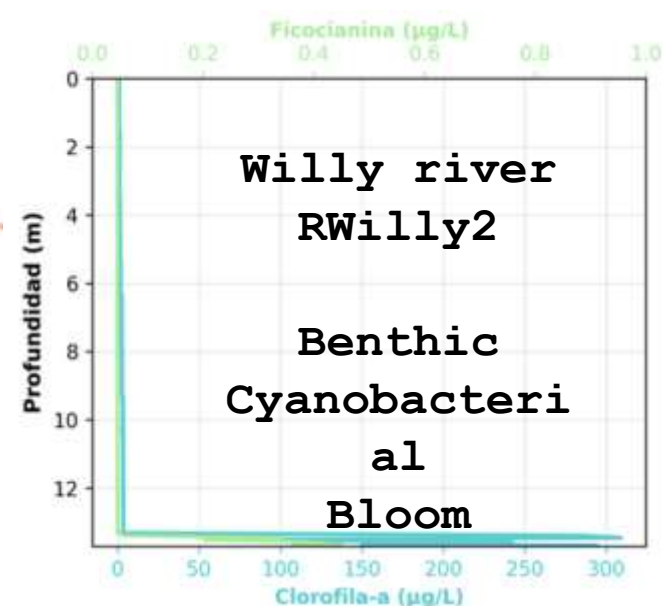
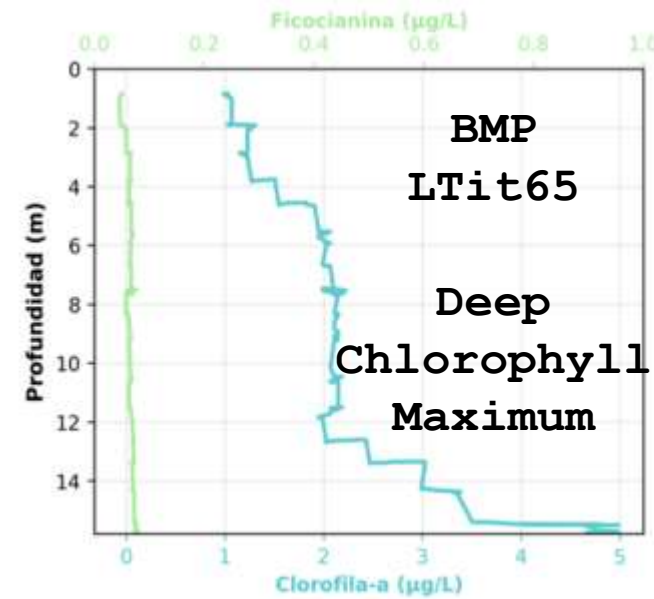
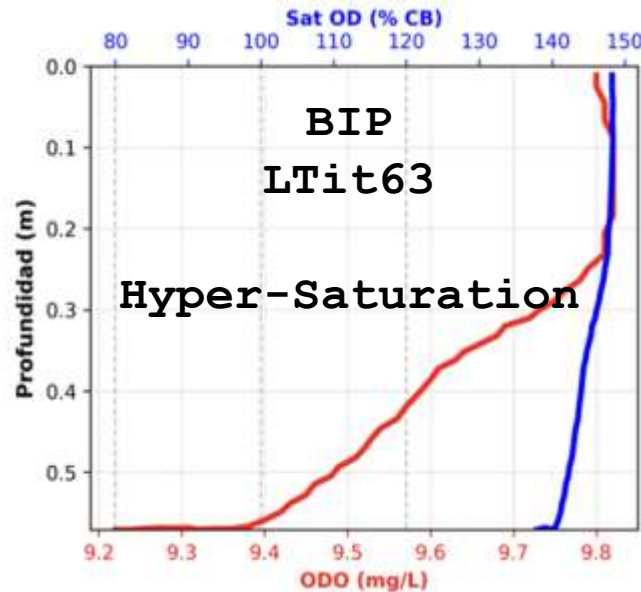
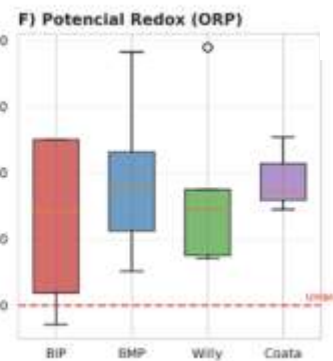
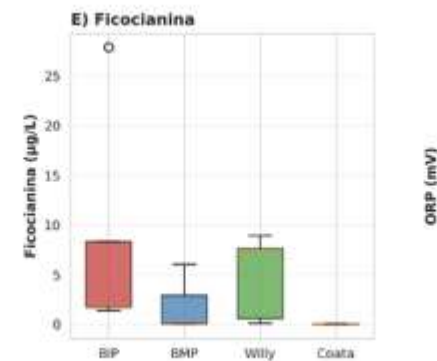
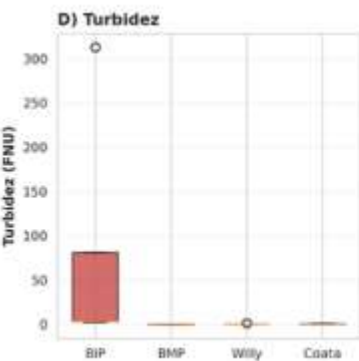
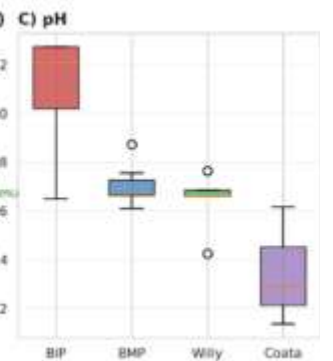
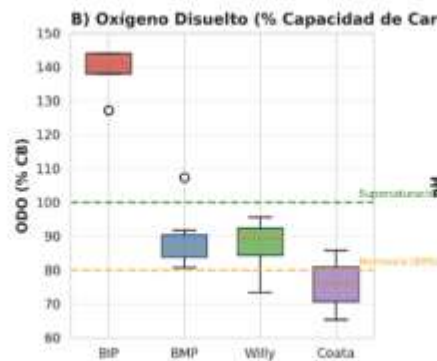
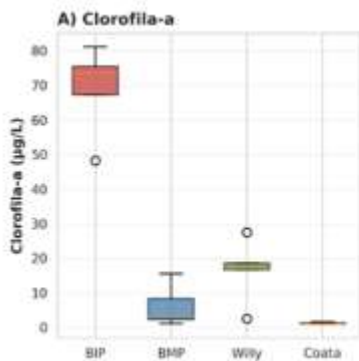
MONITORING ADVANTAGES <ul style="list-style-type: none"> Temporal and spatial tracking Does not require continuous in situ sampling Facilitates detection of algal blooms Complementary to traditional methods (OECD) 	DEVELOPMENT (Eleveld et al., 2017) <ul style="list-style-type: none"> 871 in situ Rrs spectra (Global lakes, extreme gradient) Cluster Analysis Using visible and NIR wavelengths (Sentinel-3) 	IMPLEMENTATION (SNAP/ESA Platform) <ul style="list-style-type: none"> Scheme 6C (Non-normalized): Best performance: Shallow lakes, high reflectance, sediment load. Scheme 6CN (Normalized): Best performance: Deep lakes, low reflectance. Promising for dark/CDOM. 	APPLICATION: LAKE TITICACA <ul style="list-style-type: none"> Perfect agreement between OECD and OWT classification. Significant advancement for high mountain monitoring.
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Multivariate statistical analyses

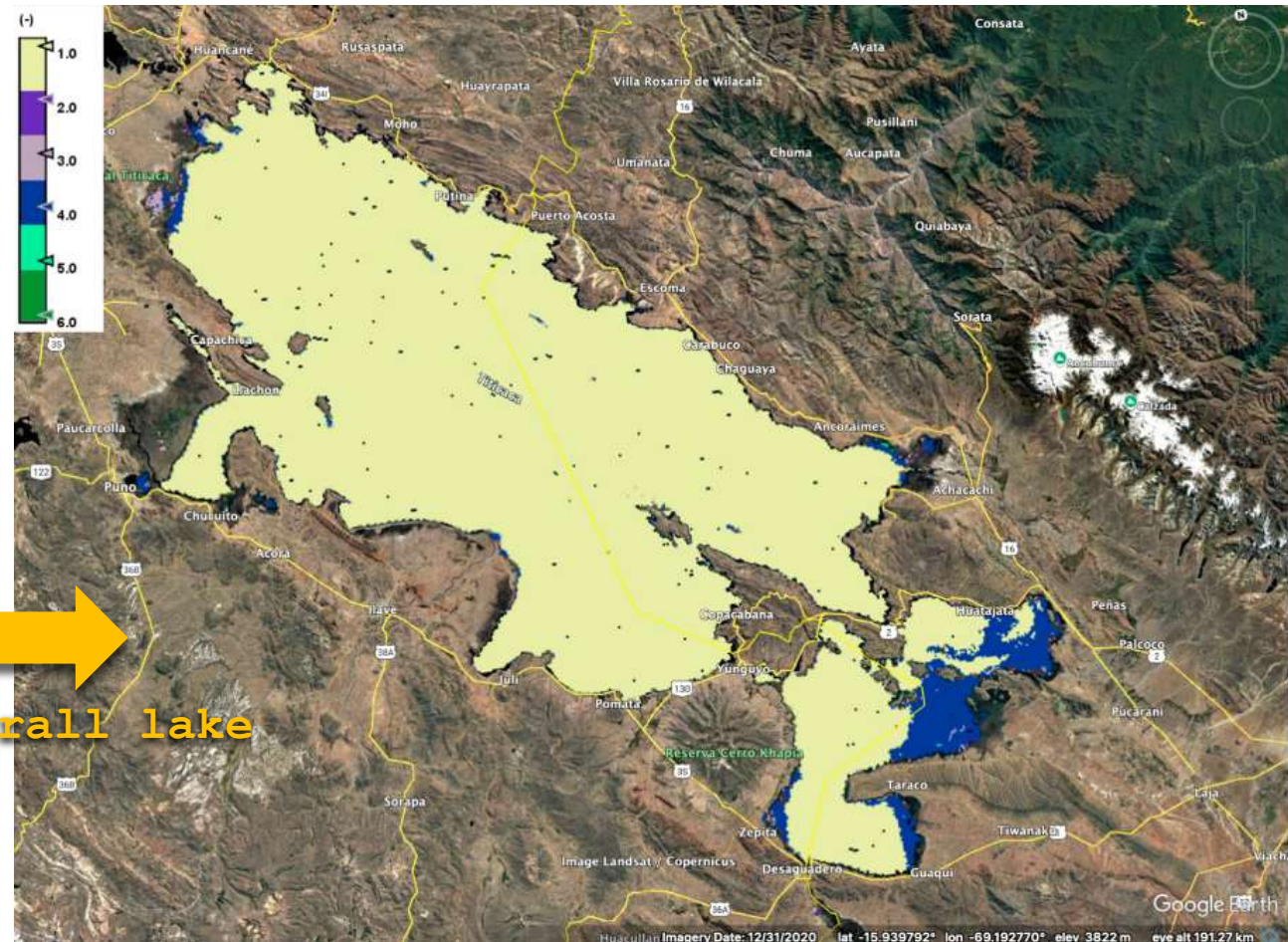


Comparative limnological variables by zones




Peculiarities by zones



OECD Trophic States vs. OWT States concordance



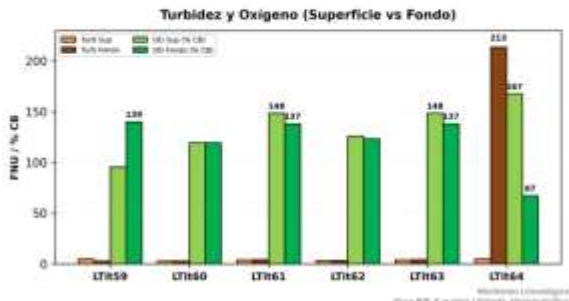
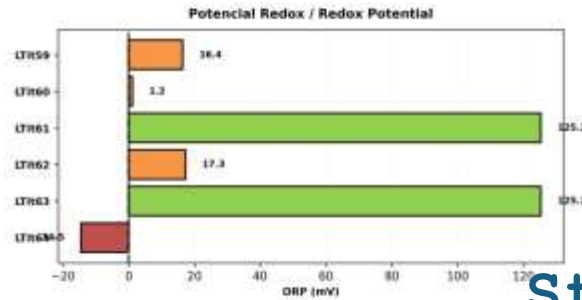
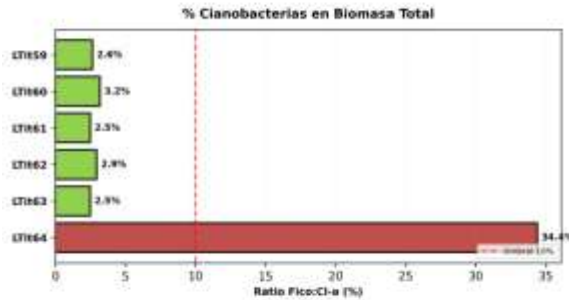
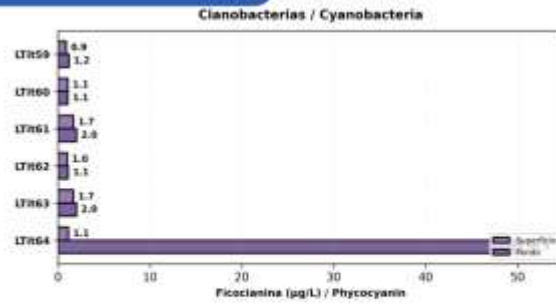
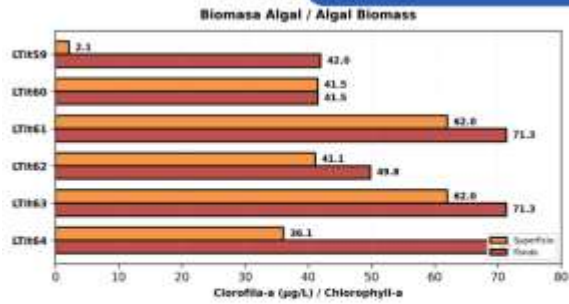
Overall lake

-  oligotrophic - OWT-1 (10)
-  mesotrophic - OWT-2 (9)
-  hyper-eutrophic - OWT-4 (7)

25 *in situ* OWT points overlaid on Sentinel-3 OWT classification image (300 m resolution, daily coverage, Aug 22, 2025)

Sentinel-3 OWT clasificación image overlaid on Google Earth map (Oct 24, 2024)

ZONA 1: BAHÍA INTERIOR DE PUNO (BIP)



Station	Trophic State
LTit59	Hipertrófico
LTit60	Hipertrófico
LTit61	Hipertrófico
LTit62	Hipertrófico
LTit63	Hipertrófico
LTit64	Hipertrófico

Infographics of key characteristics by zone

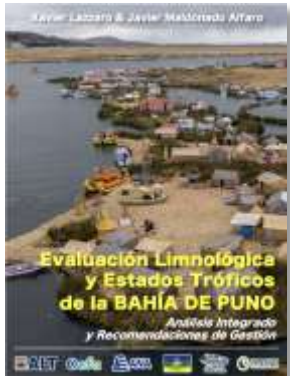
- **Fulfills ALT binational mandate:** protect ecosystem and population
- **Scarce resources:** Maximize dual impact (ecosystem + health)
- **Interdisciplinary:** Brings together limnologists, public health experts, and managers

Strategic management recommendations for public policy

PRIORITIZATION MATRIX

BALANCED Scenery: 50% ECOLOGY + 50% PUBLIC HEALTH

- **TOP PRIORITY (2 points):** LTit64 (BIP), RWilly2 (Willy)
- **HIGH PRIORITY (6 points):** RWilly5 (Willy), LTit62-LTiti2-LTit60 (BIP), LTit70 (BMP), RWilly3 (Willy)
- **MEDIUM PRIORITY (2 points):** LTit66-LTit68 (BMP)
- **LOW PRIORITY (15 points):** RWilly1 (Willy), LTit59 (BIP), DrCoat1 (Coata), RWilly4 (Willy), DrCoat2 (Coata), Ltiti61-LTiti63 (BIP), RWilly0 (Willy), LTit72-Ltiti3-LTit69-LTit67-LTit71-LTit12-LTit73 (BMP)



The Proposed Model: A 2-Tier Early Warning System

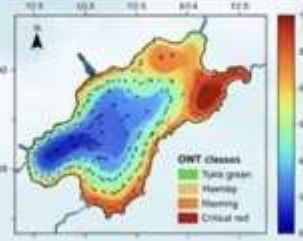
Tier 1: The Sky (Daily Continuous Watch)



ESA Sentinel-3 captures daily imagery



SNAP/C2RCC software processes atmospheric corrections



Automated OWT trophic maps generated



Zero-cost, daily binational monitoring



Triggered ONLY if anomaly detected (e.g., expanding OWT-4 class)

Tier 2: The Water (Targeted Action)



MS PlanetSolar II deploys to anomaly coordinates



YSI EXO2 probe confirms conditions in situ



Highly efficient resource allocation

Protecting the Ancestral Heritage of Lake Titicaca

- Science has identified the problem and outlined a solution