Hydrochemical characterization of the natural Tamda Lake and its environs (Middle Atlas, Morocco)

Jamal Abbach[1, *], *Hajar* El Talibi[1], *Said* El Moussaoui[1], *Hind* Cherkaoui Dekkaki[1] and *Issam* Ettabai[1]

[1]Faculty of Sciences and Techniques of Al Hociema, University of Abdelmalek Essaadi, Morocco

Abstract. The Middle Atlas region, distinguished by its diverse natural landscapes, hosts approximately forty lakes, each formed through unique geological processes, predominantly tectonic movements and karst phenomena. This research focuses on a specific case study of a lake formed by a landslide within the northern Middle Atlas. Employing both field and laboratory water analysis techniques, this study meticulously evaluates the physico-chemical parameters of the lake's water and its adjacent aquatic systems. The primary objective is to delineate the physico-chemical quality of the water in Tamda Lake and to elucidate its hydrological attributes, thereby contributing to the broader understanding of limnological dynamics in geologically diverse terrains. This investigation not only sheds light on the physico-chemical status and hydrological behavior of Tamda Lake but also enhances our comprehension of lake formation processes in the Middle Atlas, offering insights into the environmental and geological factors influencing water quality in naturally occurring lakes.

1 Introduction

The Atlas mountain range in Morocco is renowned for its rich tapestry of natural lakes, each serving as a pivotal case study for understanding the region's geological evolution. The genesis of these lakes, deeply rooted in diverse natural phenomena, offers a window into the past climatic and tectonic activities shaping the Atlas Mountains. Notably, Tamda Lake in the Middle Atlas exemplifies this diversity, having originated from a landslide event. Characterized as a ephemeral lake, its hydrology is intricately linked to the regional climatic variations, presenting fluctuating water levels that reflect the broader environmental dynamics.[1]

This study aims to conduct a thorough hydrological and hydrochemical examination of Tamda Lake and its vicinity. By leveraging field data coupled with in-depth on-site and laboratory analyses, the research seeks to characterize the water quality and unravel the environmental narratives embedded within this unique lacustrine system.

Study area

Tamda Lake, a natural lake, is situated within the Maghraoua municipality, approximately 80 kilometers south of the Taza province, nestled in a mountainous terrain where altitudes surpass 1500 meters. This region, characterized by its rugged topography, hosts the lake in a setting that is both visually striking and ecologically significant (see Figure 1).

The lake's catchment area extends over roughly 78.69 square kilometers, with geographical dimensions highlighting a maximum length of 17.16 kilometers, a width reaching approximately 9.45 kilometers, and a perimeter of about 51.93 kilometers (refer to Table 1). The elongated form of the lake, evidenced by a compactness index close to 1.6, allows for a length of up to 4.5 kilometers, showcasing its significant spatial extent within the landscape.

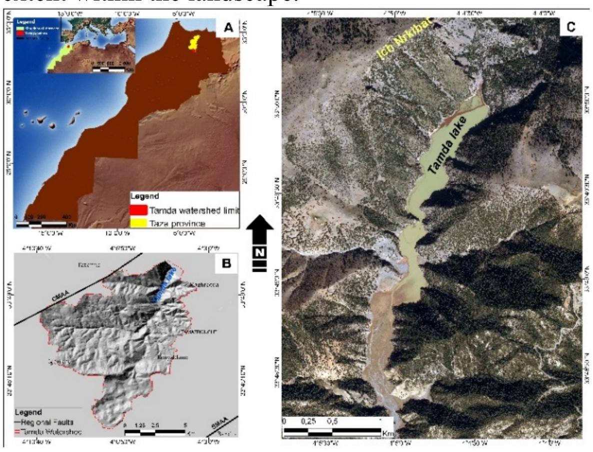

Fig. 1. General setting of the study area with the location of lake Tamda [3]

Table. 1. Dimension of the Tamda watershed

Dimension of the Tamda watershed	
Maximum length in Km	17, 16 km
Maximum width in Km	9, 45 km
perimeter in km	51,93 km
Surface in km²	78,69 km^2
The highest point	2457 m
The lowest point	1450 m

Hydrologically, Tamda Lake is predominantly nourished by alluvial inputs and direct precipitation, the latter being especially critical during the cold seasons when water availability peaks. The lake's surface area can expand to approximately 1.41 square kilometers

* Corresponding author: jamalabbach21@gmail.com

under favorable conditions. Historical data from May 2007 estimated the lake's volume at around 1.7 million cubic meters [1]. Recent measurements in April 2018 suggest an increased volume of 2.48 million cubic meters [3], indicating dynamic changes in its hydrological profile. Seasonal fluctuations are pronounced, with water levels receding in summer and the lake occasionally drying up during extended periods of heat, following a "fill-and-spill" hydrological pattern.

Geologically, the lake basin is situated at an elevation of 1500 meters, primarily composed of carbonate rock formations. This geological backdrop is complemented by lush vegetation, including cedar and evergreen oak forests that can reach heights of up to 50 meters. The dam, integral to the lake's hydrological management, spans approximately 474 meters in length and 426 meters in width, embodying a crucial infrastructure within this delicate ecosystem..

3 Regional Setting

The Tamda watershed experiences a distinctive climate, marked by very cold mountainous Mediterranean winters and moderately hot summers. This climatic pattern is shaped by westerly oceanic disturbances and the influence of Saharan continental air masses from the southeast [4]. Temperatures across the region generally remain low, averaging 11 to 12°C annually but can dip below freezing during the winter months. The peak summer months of July and August ([2]; [5]) see average maximum temperatures. Precipitation predominantly occurs as snow from autumn through to late spring, with annual averages ranging from 500 mm in the western regions near the Sebou-Inaouène confluence to 700 mm towards the east of Taza. The mountainous terrains flanking the watershed receive significantly higher rainfall, with the south-eastern peaks of Djebel Tazzeka seeing up to 1500 mm and the northern high slopes receiving slightly over 1000 mm annually. Despite the considerable variability in interannual precipitation, the region averages 60 to 70 rainy days per year. Snowmelt plays a crucial role in recharging groundwater reserves, facilitating the dissolution of limestone, and fostering the development of karst landscapes, which are prominent features of the regional geology.[1][6]

Table 2. Average annual rainfall and temperature between 1980 and 2019 (Data from National Forestry Research Center (CNRF)

Station	Lat (N)	Long (W)	Altitude (m)	Rain (mm/an)	T (°C)
Bab Boudinar	34°04’	4°07’	1570	1220	19
Tazekka	34°11’	4°12’	1380	851.4	18
Taza	34°13’	4°01’	500	524.5	23
Bou Iblane	34°14’	4°02	2500	678.6	18
Tamatroucht	34°14’	4°01’	2450	678.4	17

4 Methods

Commencing in 2018, our research adopted a seasonal sampling strategy to capture the hydrochemical dynamics during both dry and wet periods. Samples were systematically collected from various points within the lake at a depth of 50 cm, as well as from elevated positions surrounding the area. Additional samples were sourced from piezometric points downstream to enable comprehensive correlation analyses across different locations. Field measurements were conducted to assess temperature, pH, electrical conductivity, dissolved oxygen, and turbidity using an EC meter. Laboratory analyses further explored the physical, chemical, and biological attributes of the water, aiming to draw connections between the observed water quality and the structural geology of the region. This investigation was augmented by Geographic Information System (GIS) data and remote sensing techniques, focusing on the spatiotemporal dynamics of Tamda Lake.

5 Results

5.1 Hydrochemical Characterization

The comprehensive suite of laboratory analyses conducted on the waters of Tamda Lake and its adjacent areas reveals significant insights into their hydrochemical properties. The water, both from the lake and surrounding sources, is characterized by its colorless and odorless nature, indicating a lack of significant organic or inorganic contamination that could impart color or odor. The turbidity measurements, a key indicator of water clarity, range from 0.10 to 1.51 Nephelometric Turbidity Units (NTU), suggesting a generally clear water column with minimal particulate matter.

Notably, the absence of free residual chlorine underscores the natural quality of these waters, devoid of anthropogenic disinfection treatments. The pH levels, an essential parameter for assessing the acidic or basic nature of water, span from 7.4 to 7.8 within the lake, signifying a slightly basic environment conducive to aquatic life. In contrast, the broader range of pH values (6.67 to 8.40) from various sources, including wells and surface water bodies like the Sababat waterfall, highlights the diverse geochemical influences across the watershed.

Electrical conductivity, a measure of water's ability to conduct electrical current, varies between 193 and 256 μS/cm in lake waters, reflecting relatively low ionic concentrations. However, elevated conductivity levels (267 to 792 μS/cm) in other sampled locations, particularly the Tamourghout wells and a source at the dam's north flank (SAVT), suggest varying degrees of mineralization. The chloride concentrations, indicative of saline intrusion or anthropogenic pollution, remain below 71 mg/L in the lake, with slightly higher levels observed in other areas, peaking at 95 mg/L at the Tamourghout wells.

Further, the analysis of nutrients and other chemical parameters, such as ammonium, KMnO_4 oxidizability, nitrate, and nitrite, reveals minimal concentrations, well within global standards for freshwater ecosystems. However, the KMnO_4 oxidizability slightly surpassing 5 mg O_2/L in lake waters points to a moderate presence of biodegradable organic matter.

The assessment of trace metals uncovers elevated iron concentrations in both lake and well waters, contrasting with the significantly lower values in seven springs (7 STAH) and the spring (SAVT), indicating localized geochemical processes affecting iron solubility. Copper levels are generally low, except for an anomaly in the well (OCH) at Oued Arsa, which exhibits elevated copper concentrations, potentially hinting at localized mineralogical influences or anthropogenic inputs. Zinc and manganese levels are characterized as low across the sampled points, further affirming the relatively unpolluted status of the waters within and surrounding Tamda Lake.

Table 3. Physico-chemical analyses of the water in the Tamda catchment area and its surroundings; carried out by the laboratory of the Tangier-Tetouan regional directorate of the Ministry of Health.

Parameters	Reference methods	The results					Criteria for AGV
		Lake	Tamourghout well	spring		Waterfall Sababt	
				Tassiwin	Mzilaf		
odor at 25°C	NM 03-7-016	Without	Without	Without	Without	Without	3 seuils de perception à 25°C
Color	NM 03-7-018	Colorless	Colorless	Colorless	Colorless	Colorless	20 Unités Pt mg/l
Turbidity	NM 03-7-010	1.51	0.79	0.17	0.10	0.46	5 NTU
CRL		0.00	0.00	0.00	0.00	0.00	< 1mg/l et > 0.1 mg/l
Ph	NM 03-7-09	7.38	7.14	7.68	7.28	8.40	6.5< Ph < 8.5
EC	NM 03-7-011	193	430	292	379	267	2700µs/cm à 20°C
Chloride (750mg/l)	NM 03-7-024	71.00	95.85	63.90	67.45	71.00	750mg/l
Ammonium	NM 03-7-012	0.24	0.24	0.32	0.24	0.32	0.5mg/l
Oxidability with KMNO4	NM 03-7-015	5.32	0.36	1.30	0.23	1.30	5mgO2/l
Nitrite	NM 03-7-013	0.005	0.004	0.008	0.008	0.007	0.5mg/l
Nitrate	NM 03-7-014	<10	<10	<10	<10	<10	50mg/l

Table 4. analysis of the cations and some physico-chemical parameters of the water in Lake Tamda and some piezometric points downstream.

	Ph	CE (ms/cm)	Salinité (g/l)	Fe (mg/l)	Cu (mg/l)	Ca (mg/l)	Zn (mg/l)	Mn (mg/l)	Fe/Mn
P2 OCH	6.76	0.79	0.5	3.01	0.01	43.9	0.007	0.13	22.6
P2 TAMR	6.95	0.78	0.5	5.95	0.008	45.9	0.02	0.15	38.6
P3 TAMR	7.1	0.7	0.44	6.61	0.007	41.8	0.008	0.165	40.06
TAME	7.8	0.25	0.16	3.728	0.007	17.27	0.002	0.175	21.30
TAMO	7.4	0.21	0.13	4.089	0.007	12.02	-----	0.176	23.23
7 STAH	6.97	0.46	0.3	1.56	0.005	34.1	0.006	0.18	8.45
SAVT	6.84	0.77	0.5	1.8	0.007	47.9	0.02	0.2	8.8

5.2 Field Measurement Insights

Utilizing a high-precision EC meter, field measurements were systematically conducted across diverse geographical coordinates and altitudes, capturing a range of environmental conditions. These measurements, recorded at various dates and times, revealed a notable consistency in certain hydrochemical parameters, suggesting a degree of homogeneity between in-situ observations and subsequent laboratory findings. The lake's water temperature predominantly fluctuated between 18°C and 19°C, with salinity levels measured at minimal to 0.13 µS/cm, and conductivity values spanning from 145 to 208 µS/cm, as detailed in Table 5.

Further field investigations in 2021 targeted additional locations around Lake Tamda, including two specific points on the lake and two along the research route, across the contrasting seasons of May and July. These efforts aimed to corroborate the initial findings from 2018. While the general trends remained consistent, slight deviations were noted between the May and July readings, particularly in terms of temperature, ionic concentration, and total dissolved solids at the AVT source and the seven springs. Notably, Lake Tamda experienced significant water level reductions during the summer months, nearing complete drainage, as recorded in Table 6.

5.3 Eutrophication Dynamics

Eutrophication, the process resulting from excessive nutrient enrichment (notably phosphorus and nitrogen), triggers a series of ecological shifts, including heightened algal biomass and subsequent water column deoxygenation—driven by the heterotrophic decomposition of organic matter [7]. This phenomenon is particularly observable in mountain lakes, which, despite their isolation from direct anthropogenic effluents, are susceptible to nutrient influxes via atmospheric and sedimentary deposits [8]. The significant role of dissolved atmospheric inorganic nitrogen in nutrient loading within the watershed merits attention.

During the summer, Tamda Lake exhibits a distinctive green hue, a visual manifestation of eutrophication characterized by vigorous algal and planktonic activity. This seasonal transformation is primarily facilitated by the proliferation of Potamogeton pectinatus (pectinate pondweed), which extensively colonizes the lake's surface. This visual and ecological indicator underscores the impact of nutrient over-enrichment in otherwise pristine mountain lake ecosystems, highlighting the need for continued monitoring and mitigation strategies to preserve these valuable aquatic resources.

Table 5: Results obtained from some physico-chemical measurements carried out in the field in April 2018.

Samples	Altitude en m	GC	T °C	EC µs/cm
Oued Tamourghout	914	Lo: 4°02'04,67"W La: 33°53'43,33"N	23.7	515
Tamourghout well	988	Lo: 4°02'00,20" W La: 33°53'45,03"N	19.7	591
Waterfall Sababt	1105	Lo: 4°01'29,97"W La: 33°53'05,09"N	20.4	428
LAC 1	1549	Lo :4°04'27,78"W La :33°50'02,33N	19.8	202
LAC 2	1549	Lo: 4°04'26,60"W La: 33°50'04,28"N	29	208
LAC 3	1549	Lo: 4°04'25,94" W La: 33°50'03,46"N	18.8	193.4
LAC 4	1549	Lo: 4°04'25,24"W La: 33°50'01,05"N	18.9	198
LAC 5	1549	Lo: 4°04'22,77"W La: 33°49'57,94"N	19.2	235
LAC 6	1549	Lo: 33°49'55,34"W La; 33°49'55,34"N	19.4	189.2
Spring Tassiwin	1932	Lo: 4°03'45,13" W La: 33°49'31,18"N	12.9	360
Spring (?)	1280	Lo: 4°02'18,19"W La: 33°52'57,05"N	20.4	728
Spring (?)	1700	Lo: 4°03'27,86"W La: 33°49'19,27"N	18.3	504

Table 6: results of on-site measurements of physico-chemical parameters in May 2021 and July 2021.

Saison	Wells	Alti. (m)	CG	T°c	Salinity (psu)	Rési (KΩ.m)	TDS (ppm)	EC µs/cm	Waters H h(m)	Altitude z(m)	H= z-h(m)	Δ
May-21	P1	949	33.8814N 4.0487W	17.06	0.40	1.69	302.50	605.60	5.45	17.50	12.05	6.85
	P2 Sonde	949	33.8840N 4.0485W	16.50	0.34	1.60	306.50	607.40	3.88	41.00	37.12	14.03
	P1 Tamr	899	33.8930N 4.0389W	15.60	0.40	1.70	301.60	605.40	19.73	11.04	8.33	1.83
	P2 Tamr	887	33.8960N 4.0335W	14.80	0.34	1.64	295.40	608.30	2.44	5.45	3.01	0.63
	P3 Tamr	898	33.8956N 4.0337W	16.50	0.30	1.85	263.60	535.90	0.83	7.13	6.30	0.93
	P4 Tamr	898	33.8956N 4.0337W	16.80	0.30	1.87	266.60	538.90	0.61	6.79	7.40	2.36
Jul-21	P1	949	33.8814N 4.0487W	18.11	0.43	1.64	302.56	605.67	12.40	17.60	5.20	
	P2	949	33.8840N 4.0485W	17.53	0.37	1.52	307.50	608.47	17.91	41.00	23.09	
	P1 Tamr	899	33.8930N 4.0389W	15.66	0.47	1.56	303.60	607.48	4.54	11.04	6.50	
	P2 Tamr	887	33.8960N 4.0335W	15.87	0.39	1.50	297.47	609.39	3.70	5.45	2.38	
	P3 Tamr	898	33.8956N 4.0337W	17.37	0.39	1.88	265.50	536.70	1.76	7.17	5.37	
	P4 Tamr	898	33.8953N 4.0341W	16.92	0.36	1.75	268.30	537.86	1.75	6.79	5.04	

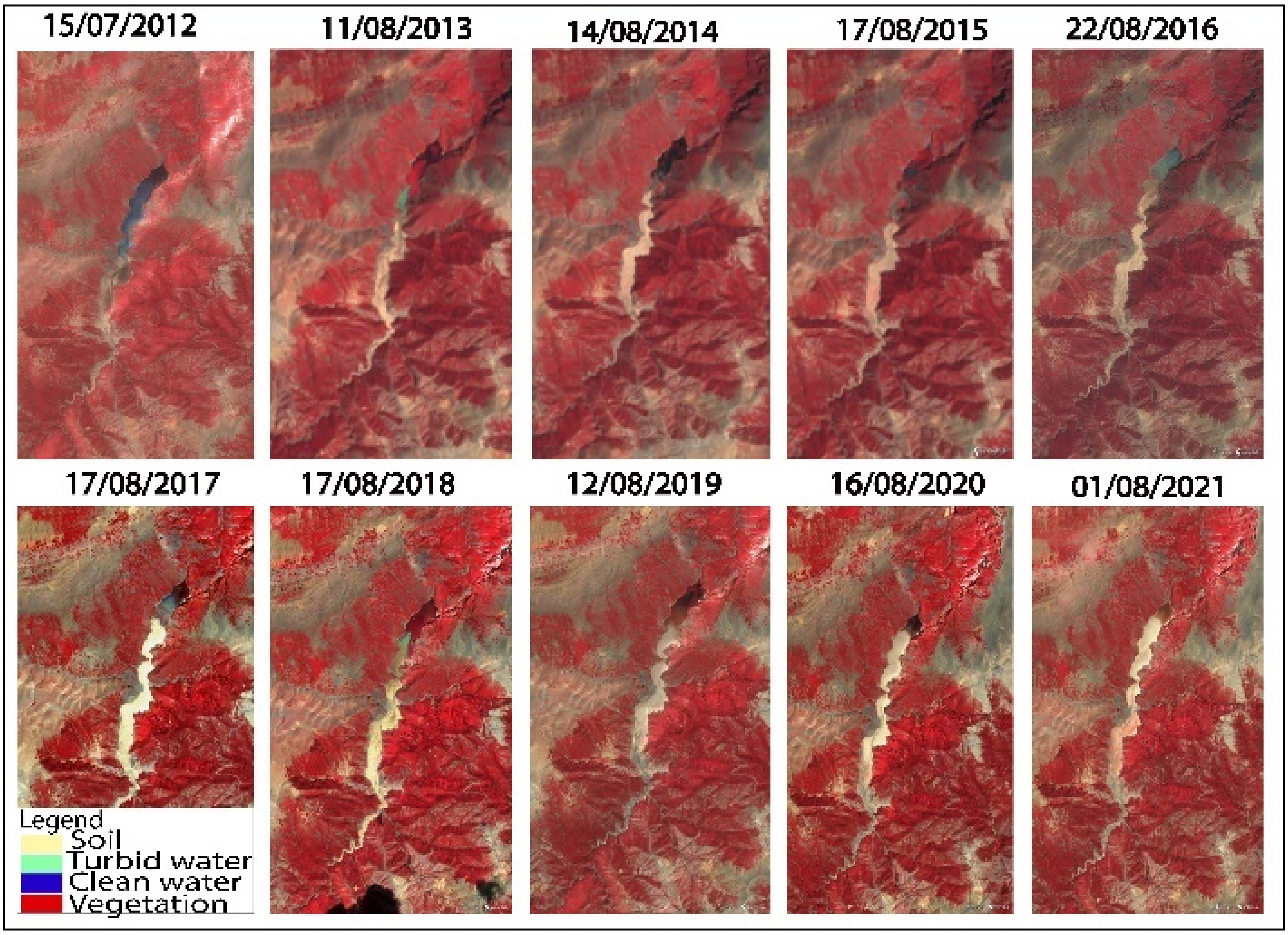

Fig. 2. False colors composition images illustrating eutrophication of the lake during the warm seasons between 2012 and 2021.

6 Discussion

The hydrochemical profile of Tamda Lake is predominantly influenced by its calco-magnesian composition, relative alkalinity, and high oxygenation levels, a direct consequence of the carbonate bedrock within its basin. This interaction between water chemistry and geological substrates, encompassing karst processes, fluvial contributions, and atmospheric deposition, underscores the significant role of the lake's physiographic and lithologic setting in shaping its water quality ([3]; [9]). The analytical outcomes affirm the lake's water quality as exceeding the standard thresholds for purity, reflecting its pristine condition relative to established maximum permissible values for various constituents.

Considering Tamda Lake's geological genesis, ephemeral hydrology, endorheic nature, and the lithological characteristics of its contributing watershed, a comprehensive understanding of regional water quality emerges. The analyses reveal the exceptional quality of water within the lake and its broader catchment, marked by constituent concentrations significantly below maximum allowable limits. These findings, documented across Tables 6.1 to 6.4, suggest a uniform hydrochemical identity across the region, albeit with notable exceptions like the Taswim spring on the Mleg ridge. This spring, distinguished by its superior physico-chemical parameters and situated at an altitude of 1800 meters, epitomizes the high-quality water resources endemic to the area.

The observed eutrophication during dry periods highlights an ecological disequilibrium, primarily attributed to excessive phosphorus and nitrogen concentrations fostering heightened organic matter production. Such imbalances, evidenced by increased $KMnO_4$ oxidizability, point to escalated biological activity, particularly during the warmer months [10].

Furthermore, the inherent characteristics of the catchment's carbonate composition, its elevated and remote locale, free from anthropogenic pollutants, and the extreme weather patterns featuring copious precipitation, collectively fortify the water quality at various elevated locales within the watershed and its environs. This isolated, yet dynamic, environmental setting facilitates the sustenance of high-quality water resources, despite the challenges posed by natural eutrophication processes.

The distinctive red hue observed in water during dry spells, as captured through false-color imaging, signals intense biological activity, likely spurred by eutrophication. This condition is attributed to the abundance of organic matter, derived from sedimentary deposits and forest detritus, enriching the upstream watershed. Such visual and biochemical indicators serve as critical markers for understanding the ecological and hydrochemical dynamics at play within Tamda Lake's ecosystem, offering insights into its seasonal and spatial variability in water quality.

7 Conclusion

In this study, we embarked on a comprehensive examination of water samples from Tamda Lake and its vicinity, adopting a non-seasonal approach to our sampling regimen. Our primary objective was to scrutinize the physico-chemical attributes of the water, aiming to unveil the intrinsic quality of this vital resource. The findings from our analyses have demonstrated a clear linkage between the water quality and the geomorphological features of the study area, including its pronounced karst landscape. Such geological characteristics have played a pivotal role in shaping the hydrological dynamics and contributing to the region's aquatic development.

Despite the insights gained, it becomes evident that a more structured approach to monitoring—encompassing seasonal variations and employing targeted analytical methods—would significantly enhance our understanding of the lake's hydrological patterns and the temporal shifts in its water volume. Seasonal monitoring would not only provide a finer resolution of data but also enable the identification of cyclic trends and potential anthropogenic impacts on water quality. Future research efforts should, therefore, prioritize establishing a systematic observation framework that captures the seasonal nuances of the lake's hydrochemistry. This would offer a more nuanced perspective on the ecological and hydrological processes at play, facilitating informed conservation and management strategies for Tamda Lake and similar aquatic ecosystems.

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