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Water Quality and Anthropogenic Pressures in Xinjiang's Alpine Lakes: A Comparative Study of Tianchi, Sayram, and Bosten

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Abstract:

The alpine lakes of Xinjiang, China, represent critical ecological and economic resources facing growing anthropogenic pressures. This study conducts a comparative water quality assessment of Tianchi, Sayram, and Bosten Lakes to evaluate their ecological status and identify major drivers of environmental stress. Water samples collected during the peak tourism season were analyzed for nutrients, organic matter, heavy metals, and physicochemical indicators. The results reveal distinct profiles: Tianchi Lake exhibited oligotrophic characteristics with low nutrient concentrations, undetectable heavy metals, and absence of fecal coliforms, reflecting the effectiveness of stringent protective management. In contrast, Bosten Lake showed signs of eutrophication, and its Chemical Oxygen Demand indicates significant organic pollution from non-point sources; Sayram Lake displayed geochemical anomalies, characterized by elevated arsenic concentrations and alkaline pH, likely influenced by regional geology, together with moderate organic pollution. This study concludes that the environmental challenges facing these lakes are different. Tianchi requires consistent management to preserve its state, Bosten urgently needs integrated watershed management to control diffuse pollution, and Sayram demands further investigation into the source of arsenic and the ecological impacts of its high pH. The results highlight the necessity for lake-specific conservation strategies to ensure the long-term sustainability of these vital ecosystems amidst increasing human activity.

Keywords: Xinjiang Alpine Lakes; Water Quality; Anthropogenic Impact; Sustainable Management.

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1. Introduction

In contemporary society, tourism has emerged as a major form of leisure and a significant driver of economic development. However, the rapid growth of tourist flows exerts considerable pressure on the environment, particularly in ecologically sensitive regions. This challenge is especially evident in Xinjiang, China, where the tension between economic development and environmental conservation has become increasingly pronounced. Local governments rely heavily on tourism for economic growth, often at the expense of natural resources. In recent years, Xinjiang's tourism industry has expanded substantially, largely driven by its unique natural landscapes. Among its most valuable assets are the alpine lakes, which function not only as important ecological resources but also as key contributors to the tourism economy. For example, Tianchi Lake, situated in the Tianshan Mountains, is known for its clear waters and alpine scenery [1]; Sayram Lake, often referred to as "the last tear of the Atlantic Ocean" [2]; and Bosten Lake, the largest inland freshwater lake in China, all play vital roles in supporting regional economies and ecosystems. These lakes have become major tourist attractions, with Xinjiang as a whole welcoming approximately 300 million visitors in 2024, a 14% increase compared to 2023 [3]. The growing scale of tourism, combined with other intensive human activities, has introduced increasing anthropogenic pressures that extend beyond the tourism sector alone. The rapid development of infrastructure—including hotels, recreational facilities, and transportation networks—has frequently occurred without adequate environmental safeguards, motivated by the pursuit of economic revenue. In addition, agricultural expansion, livestock grazing, and land development exert further pressure on the fragile aquatic ecosystems. As a result, these lakes face multiple threats, including nutrient enrichment, sewage discharge, chemical contamination, and geochemical alterations, all of which pose substantial risks to water quality and ecological integrity. Although several studies have investigated individual lakes in Xinjiang, comprehensive comparative analyses remain limited. Most existing research has concentrated on single water bodies, leaving a knowledge gap in understanding the broader relationship between human activities and water quality degradation across Xinjiang's key lakes [1–4]. To address this gap, the present study undertakes a comparative analysis of three representative alpine lakes—Tianchi, Sayram, and Bosten. Specifically, this research aims to (i) quantify differences in 17 critical water quality parameters to identify pollution patterns and trends, (ii) assess the correlation of water quality conditions with anthropogenic activities, agricultural practices, and geochemical factors, and (iii) identify priority parameters requiring continuous monitoring and management to ensure ecological sustainability. By examining these lakes in a comparative framework, this study seeks to provide actionable insights for policymakers, environmental managers, and local stakeholders. The findings will contribute to the development of lake-specific conservation strategies that balance economic development with ecological protection, thereby supporting the long-term sustainability of Xinjiang's alpine lake ecosystems.

2. Method

This study focused on three alpine lakes in Xinjiang, China—Tianchi, Sayram, and Bosten—selected for their ecological importance, cultural significance, and varying levels of anthropogenic pressure. Tianchi Lake is a major tourist destination equipped with pioneering environmental management practices, including physical barriers to minimize direct human–water contact. Sayram Lake is characterized by expanding tourism infrastructure and distinctive geochemical properties, representing a moderate level of anthropogenic influence. In contrast, Bosten Lake, the largest inland freshwater lake in China, experiences combined pressures from tourism development, agricultural runoff, and potential industrial activities.Water sampling was conducted once during the peak tourism season (August 2024) to capture conditions under vast anthropogenic pressure. For each lake, integrated surface water samples (about 0.5 m depth) were collected from a central, open-water location to ensure representation of overall lake conditions three times per lake. Samples were collected and stored in pre-cleaned designated lid-sealed water sampling bad, and transported to the laboratory for analysis within 24 hours to ensure sample integrity [4]. The test results are listed in Table1:

Table 1. Test Results

No.	Parameters	Tianchi	Sayram	Bosten
0	Sample Appearance	Colorless, transparent	Colorless, transparent	Colorless, turbid
1	Ammonia Nitrogen (mg/L)	0.062	0.046	0.072
2	Total Phosphorus (mg/L)	0.02	0.03	0.03

3	Total Nitrogen (mg/L)	0.59	0.52	0.53
4	Chemical Oxygen Demand (mg/L)	4L	18	20
5	Dissolved Oxygen (mg/L)	8.84	8.72	7.74
6	Fluoride (mg/L)	0.06	0.6	0.38
7	Permanganate Index (mg/L)	1	3.4	4.6
8	Fecal Coliforms (MPN/L)	Not detected	Not detected	Not detected
9	Hexavalent Chromium (mg/L)	0.004L	0.006	0.01
10	pH (dimensionless)	7.3	8.9	7.4
11	Lead (Pb) (μg/L)	2.5L	2.5L	2.5L
12	Cadmium (Cd) (μg/L)	0.5L	0.5L	0.5L
13	Copper (Cu) (mg/L)	0.05L	0.05L	0.05L
14	Zinc (Zn) (mg/L)	0.05L	0.05L	0.05L
15	Mercury (Hg) (μg/L)	0.04L	0.04L	0.04L
16	Arsenic (As) (μg/L)	0.3L	8.3	2.4
17	Selenium (Se) (μg/L)	0.4L	0.4L	0.4L
No.	Parameters	Tianchi	Sayram	Bosten

Table 2. List of Inspection Items and Their Inspection Basis

No.	Parameter	Standard Method Name and Code		Detection Limit
1	Ammonia Nitrogen	Water Quality - Determination of Ammonia Nitrogen - Nessler's Reagent Spectrophotometry (HJ 535-2009)	0.025 mg/L	
2	Total Phosphorus	Water Quality - Determination of Total Phosphorus - Ammonium Molybdate Spectrophotometry (GB 11893-1989)	0.01 mg/L	
3	Total Nitrogen	Water Quality - Determination of Total Nitrogen - Alkaline Potassium Persulfate Digestion UV Spectrophotometry (HJ 636-2012)		0.05 mg/L
4	Chemical Oxygen Demand	Water Quality - Determination of Chemical Oxygen Demand - Dichromate Method (HJ 828-2017)	4 mg/L	
5	Dissolved Oxygen	Water Quality - Determination of Dissolved Oxygen - Electrochemical Probe Method (HJ 506-2009)	0.2 mg/L	
6	Fluoride	Water Quality - Determination of Fluoride - Ion Selective Electrode Method (GB 7484-87)	0.05 mg/L	
7	Permanganate Index	Water Quality - Determination of Permanganate Index (GB 11892-1989)	0.5 mg/L	
8	Fecal Coliforms	Water Quality - Determination of Fecal Coliform - Multi-Tube Fermentation Method (HJ 347.2-2018)	20 MPN/L	
9	Hexavalent Chromium	Water Quality - Determination of Hexavalent Chromium - Diphenylcarbazide Spectrophotometry (GB 7467-1987)	0.004 mg/L	
10	pH	Water Quality - Determination of pH Value - Electrode Method (HJ 1147-2020)		/
11	Lead (Pb)	Standard Examination Methods for Drinking Water - Part 6: Metal and Metalloid Indicators (GB/T 5750.6-2023, Method 14.1)		2.5 μg/L
12	Cadmium (Cd)	Standard Examination Methods for Drinking Water - Part 6: Metal and Metalloid Indicators (GB/T 5750.6-2023, Method 12.1)		0.5 μg/L
13	Copper (Cu)	Water Quality - Determination of Copper, Zinc, Lead, and Cadmium - Atomic Absorption Spectrophotometry (GB 7475-1987, Direct Method)		0.05 μg/L

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14	Zinc (Zn)	Water Quality - Determination of Copper, Zinc, Lead, and Cadmium - Atomic Absorption Spectrophotometry (GB 7475-1987, Direct Method)		0.05 μg/L
15	Mercury (Hg)	Water Quality - Determination of Mercury, Arsenic, Selenium, Bismuth, and Antimony - Atomic Fluorescence Spectrometry (HJ 694-2014)		0.04 μg/L
16	Arsenic (As)	Water Quality - Determination of Mercury, Arsenic, Selenium, Bismuth, and Antimony - Atomic Fluorescence Spectrometry (HJ 694-2014)		0.3 μg/L
17	Selenium (Se)	Water Quality - Determination of Mercury, Arsenic, Selenium, Bismuth, and Antimony - Atomic Fluorescence Spectrometry (HJ 694-2014)		0.4 μg/L
No.	Parameter	Standard Method Name and Code		Detection Limit
1	Ammonia Nitrogen	Water Quality - Determination of Ammonia Nitrogen - Nessler's Reagent Spectrophotometry (HJ 535-2009)	0.025 mg/L	

A total of 17 water quality parameters were analyzed according to Chinese National Standard Methods (GB) and Environmental Industry Standards (HJ) by the accredited laboratory of Xinjiang Science Fair Environmental Monitoring Co., Ltd. The parameters, methods, and detection limits are summarized in Table 2Results & Analysis.

3. Method for data detection:

The water quality data from the three lakes reveal distinct environmental conditions, ranging from near-pristine to significantly impacted.

Tianchi Lake presents a profile indicative of an ecosystem in excellent health conditions, largely insulated from severe pollutant loading. First, the sample's description as "colorless and transparent" provides immediate visual confirmation of its high quality. This is substantiated by several key indicators: the concentrations of Total Nitrogen (TN) is 0.59 mg/L and Total Phosphorus (TP) is 0.02 mg/L, and these are highly favorable. TP is the primary indicator of a lake's trophic state; concentrations below 0.03 mg/L are typically considered low and are associated with clear, oxygen-rich, oligotrophic waters that are resistant to algal blooms [5]. Tianchi's TP value of 0.02 mg/L is well within this healthy range, while the TN level suggests only minimal nutrient enrichment, potentially from natural background levels or limited runoff from the surrounding watershed. This low nutrient load is further supported by the minimal presence of organic matter, as demonstrated by a Chemical Oxygen Demand (COD) below the detection limit (<4 mg/L) and a very low Permanganate Index of 1.0 mg/L. Perhaps most significantly, all tested heavy metals and toxic elements, including Lead (Pb), cadmium (Cd), copper (Cu), zinc (Zn), mercury (Hg), arsenic (As) and selenium (Se), and Hexavalent Chromium(CrVI), were reported below their detection limits, indicating a complete absence of significant industrial contamination. Furthermore, the fact that Fecal Coliform was not detected confirms there is no measurable contamination from human or animal sewage. In summary, the data suggests that Tianchi is a pristine, oligotrophic lake.

In contrast, the water data of Bosten Lake indicates an ecosystem under environmental stress, likely in the early stages of eutrophication. The sample's marked transparent and turbid, which are an initial indication of such pressure, often pointing to suspended algal cells, sediments or pollutants. Then, the chemical data confirms this cue. The TP level of 0.03 mg/L is positioned precisely at the critical threshold for potential eutrophication. When combined with a TN level of 0.53 mg/L, a sufficient nutrient base exists to support substantial algal productivity which is treating a potential eutrophication in the lake. This concern is accompanied by its COD of 20 mg/L. In China, the quality of surface water is officially classified into five categories (Class I to Class V) under the national standard GB 3838-2002 "Environmental Quality Standards for Surface Water"[6-7]. Class III is designated for centralized drinking water sources, fishing, and aquatic ecosystems, setting the upper limit for COD at 20 mg/L [6]. Bosten Lake's measured COD is therefore precisely at this threshold. This places the lake in a precarious position, as any further increase in organic pollution would cause it to fall below the standard and be classified as Class IV. This value provides definitive evidence of a substantial input of organic pollutants. This conclusion is further supported by the elevated Permanganate Index of 4.6 mg/L. The most probable sources for this organic load are consistent with the lake's watershed activities, including fertilizers or livestock waste runoff and organic matter from tourists. Another point of difference from Tianchi is the measurable presence of Arsenic at 2.4 μg/L. Although still within safety standards, its detectable presence suggests a potential contamination source in the watershed. The Dissolved Oxygen (DO) level at 7.74 mg/L, which is still healthy, could be an early sign of increased microbial activity consuming oxygen to break down the high organic content. Collectively, these parameters paint a picture of the Bosten lake containing a significant amount of external inputs, pushing it toward a eutrophic state.

Sayram Lake, however, presents a more complex and anomalous profile that can not be categorized in a simple way. The sample was "colorless and transparent," suggesting good clarity, but the chemical data reveals unique stressors. The nutrient levels where TN is at 0.52 mg/L and TP is at 0.03 mg/L are nearly identical to Bosten's, showing a similar level of nutrient content which is at a eutrophic state. This is supported by a high COD of 18 mg/L, signaling a notable level of organic load. Sayram Lake's condition is defined by two unusual chemical anomalies. The first is a high Arsenic at 8.3 μg/L- higher than that of the other lakes and signals a distinct environmental influence. The potential sources of this arsenic could be geogenic: naturally occurring from the weathering of arsenic-rich minerals and rocks in the surrounding watershed and leaching into the lake through groundwater or surface runoff. But it could also be anthropogenic: human activities such as historical mining operations, the use of arsenic-based pesticides in agriculture, or discharges from certain industrial processes. The second anomaly is the highly alkaline pH of 8.9, and water as alkaline as Sayram's can stress aquatic organisms because aquatic organisms typically adapt to pH between 6.5 and 8.5.This high alkalinity is most commonly caused by the surrounding geology; when water flows over or through rocks like limestones, it dissolves them, releasing minerals that make the water more basic. A consequence of this high pH is that it can increase the toxicity of ammonia in the water to aquatic lives. In conclusion, addressing these specific issues is essential for preserving the lake's ecological balance.

A comparison of the parameters reveals a clear gradient of ecosystem health and different types of environmental pressure of each lake. This comparison tells the relative states and unique challenges that Tianchi, Bosten, and Sayram Lakes have been facing. Tianchi consistently demonstrates the most favorable results across almost all standards. In contrast, both Bosten and Sayram Lakes show clear signs of elevated organic levels, since they have high COD values. However, their impacts diverge significantly. Bosten Lake's profile is classic of non-point source pollution, where rainfall and snow run through the ground and pick up natural and human pollutants[7]. Sayram Lake is characterized by its geochemical anomalies. Its primary concerns are the exceptionally high arsenic concentration and alkaline pH, which suggest a different set of factors, likely rooted in its specific geology.

Tianchi has a relatively good quality of water, because of its very low nutrient levels, little organic pollution, absence of heavy metals, and lack of fecal bacteria create a profile of an oligotrophic ecosystem which is a healthy environment. This state is a significant achievement and is a direct result of proactive management practices that is observed on-site. Practices such as constructing viewing platforms set back from the shoreline and installing barriers to prevent direct tourist contact with the water seem highly effective, drastically reducing the direct input of pollutants from humans such as sunscreens, food, waste, and feces. Therefore, Tianchi stands as a powerful example of how intense tourism activities and environmental preservation can successfully coexist through deliberate infrastructures and regulations.

In contrast, both Bosten and Sayram Lakes show alerts of environmental impact, though the nature and origin of this impact are fundamentally different. The most direct evidence of this is their elevated COD values—18 mg/L in Sayram and 20 mg/L in Bosten—which are about 5 times higher than Tianchi's. COD measures the amount of oxygen required to break down organic matter in the water, and high values mean there is a significant amount of pollution from substances like sewage, fertilizer, or plant decay that bacteria must decompose and consume oxygen stressing aquatic life [8].

However, the similarity between the two lakes ends with the presence of organic pollution. Bosten Lake's situation is a non-point source pollution which means pollution do not come from a single pipe or factory, but rather from many diffuse sources across that region. Bosten's combination of high turbidity, a high organic content, and elevated nutrient levels points directly to mixed pressures. Agricultural activities—such as fertilizer runoff from farms and waste from livestock—are likely a major contributor, and this is compounded by organic waste from its substantial tourism industry. The parameters suggest that the diffusion of pollutants is washed into the lake from various sources, making it difficult to control. Sayram Lake, meanwhile, presents a more complex and abnormal condition. Its most defining and concerning characteristics are its geochemical anomalies. The first is an exceptionally high Arsenic concentration, which is many times higher than in the other lakes. There is little knowledge about the source of this arsenic content, so it could be geogenic or anthropogenic. The second anomaly is a highly alkaline pH of 8.9, which is approaching the maximum pH of what most aquatic life can tolerate. This is likely caused by the natural dissolution of carbonate rocks in the surrounding mountains, which make the water more basic. For fish, this high pH is a direct physiological stressor. Crucially, high pH dramatically increases the toxicity of ammonia, a common waste product, by converting more of it into

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its harmful, un-ionized form (NH_3), which can quickly become lethal, and it damages their gill tissue, impairing their ability to breathe and maintain a healthy salt-to-water balance in their bodies.

4. Conclusion

This study demonstrates that each of the three lakes faces distinct environmental challenges, requiring tailored management approaches. Tianchi Lake is in the most favorable condition, but maintaining strict protective measures remains essential for preserving its water quality. Bosten Lake, by contrast, is affected by pollution from multiple diffuse sources, primarily agricultural runoff and tourism-related waste. Addressing these issues calls for the adoption of more sustainable agricultural practices, including the use of environmentally friendly fertilizers, improved waste management systems for tourism activities, and innovative measures to limit pollutant inflow into the lake. Sayram Lake represents a special case due to its elevated arsenic concentrations and high alkalinity, although the specific origins of these anomalies remain uncertain.

Human activities influence aquatic ecosystems in diverse ways, and safeguarding these lakes requires differentiated solutions. The findings highlight the importance of continuous monitoring of chemical parameters, not only in Xinjiang but also in other regions, to track changes and guide adaptive management strategies. At a broader scale, balancing the economic benefits of tourism with the imperative of environmental protection is critical. By applying lake-specific strategies—continuing protective management for Tianchi, implementing pollution control for Bosten, and investigating and mitigating geochemical stressors in Sayram—policymakers and environmental scientists can promote the long-term sustainability of these essential freshwater resources for both ecological integrity and human use.

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