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Mining Impacts on Drinking Water Quality in Chumar Bakhoor Sumayar Nagar A Stratified Glacier to Community Assessment

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Abstract

Purpose: Mining in high mountain catchments can degrade downstream water quality by increasing suspended solids and mobilizing dissolved ions. This study evaluates how gemstone extraction at Chumar Bakhoor influences drinking-water indicators along a glacier–mine–community transect in Sumayar Nagar, Gilgit-Baltistan. **Research design, data and methodology:** A stratified design was implemented on 9 September 2024 with nine grab samples from glacier source waters, active mining flows, and downstream community channels. Physicochemical parameters were measured for pH, electrical conductivity, total dissolved solids, turbidity, hardness as calcium carbonate, a salinity proxy, chloride, and nitrite, and interpreted against WHO, PSQCA, and ANEQS guideline values. **Results:** Mean pH was near neutral at 7.40. Ionic strength rose sharply at the mine, with electrical conductivity peaking near 1,578 microsiemens per centimeter and a cross-site mean of 705.67. Total dissolved solids averaged 278 milligrams per liter and reached 564 to 566 in mining waters. Turbidity was greatest at the mine at 307 to 309 nephelometric turbidity units and averaged 153 across sites, far above potability criteria. Chloride remained low. Nitrite increased at the mine to 0.6 to 0.7 milligrams per liter, while glacier and community waters were near detection. Hardness was very low at about 2.5 to 2.7 milligrams per liter across sites. **Conclusions:** Mining is the dominant driver of observed deterioration; without treatment and improved practices, waters influenced by mining are unsuitable for direct consumption.

Keywords : Water quality, Glacier-fed, Mining impacts, drinking-water indicators

JEL Classification Code : K32, Q25, Q53, R11

1. Introduction

Access to clean and safe drinking water remains a persistent public-health and development challenge, particularly where rapid population growth and diffuse

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waste disposal elevate pressures on limited freshwater resources (WHO, 2004; Kulshreshtha, 1998). In mountainous regions, glacier fed catchments are often perceived as pristine, yet their quality is governed by natural controls and by human activities that act along short and steep hydrological pathways connecting hillslopes, channels, and community intakes. In Pakistan's Gilgit–Baltistan, snow and ice melt supply most domestic needs through lakes, ponds, streams, and small distribution canals; however, the absence of engineered waste management and the proximity of settlements and work sites to drainage lines increase vulnerability to contamination (Aziz, 2005).

Regional assessments from Gilgit–Baltistan consistently report exceedances in key indicators of potability. Studies document elevated turbidity, total hardness, total alkalinity, anions, and fecal contamination by Escherichia coli in surface waters used by communities (Ahmed et al., 2012; Din et al., 2017; Shedayi et al., 2015; Ali and Rubina, 2018). These findings indicate that simple assumptions of safety in glacier-influenced systems are unwarranted and that anthropogenic pressures near settlements can degrade water quality at the point of use. Within this context, the Sumayar Valley presents a critical case. Glacier melt feeds the Mamubar Stream before its confluence with the Hunza and Nagar rivers, while artisanal gemstone extraction at Chumar Bakhoor operates seasonally on steep slopes above central Sumayar. Waste rock, adits, and access paths lie close to meltwater channels, creating pathways for suspended solids and dissolved constituents to enter surface waters during the mining window.

Drinking water benchmarks provide the interpretive frame for assessing such risks. Pakistan's National Standards for Drinking Water Quality specify organoleptic acceptability and numerical limits for priority chemical species, supporting compliance assessments by local authorities. The World Health Organization guidelines define health based values for chemicals, recommend operational ranges for pH that maintain distribution system stability, and stress the need to achieve very low turbidity prior to disinfection because particulate matter interferes with microbial inactivation (WHO, 2022). Together, these references guide the interpretation of field and laboratory data in data poor, high altitude settings such as Sumayar

This study addresses a defined problem and its local significance. Mining operations at Chumar Bakhoor may be altering the quality of water that downstream communities rely upon, yet the magnitude and spatial pattern of this influence have not been rigorously documented for Sumayar Valley. Establishing an evidence base is essential for protection of public health and for practical management in a remote mountain environment that depends on glacier derived flows. Accordingly, the study aims to determine whether seasonal gemstone extraction measurably degrades drinking water indicators along the pathway from glacier sources through mining reaches to community channels, to characterize the spatial distribution of any contamination with distance from mining activity, and to benchmark observed parameters against national and international standards so that actionable guidance for risk management can be provided.

2. Literature Review

Life requires water to survive. On Earth, it seems to be abundantly accessible. But 97.5 percent of it is saltwater, and only around 2.5 percent is fresh water. Water has an important effect on human health. Since humans must, at the most basic level, consume a minimum amount of water each day in order to survive, access to some form of water is essential to life. The primary drivers of the continuous rise in water use are population growth and rising demands in domestic services, industry, and agriculture. Integrated water management has a major impact on sustainability and long-term protection. Clean water is a resource that humans need, yet drinking water contamination is dangerous. done in an effort to save drinking water. The fundamental right to consume water belongs to everyone. The study looked at the quality of drinking water in Kadegaon Tehsil, Maharashtra. For this determination, series of physiological and biological parameters were used, and the outcomes were compared to allowable limits. Between August 1 and October 10, 2016, samples were collected from two main sources: well water and bore well water. The premise of the investigation was that Kadegaon City's water was unsuitable for cooking and drinking. (Ghimire et al.2013)

The local population's household needs can be met with the water from such resources. The various facets of the Himalayan surface water supplies fed by glaciers have been the subject of a few studies. Researchers discovered that the concentrations of physical, chemical, and biological factors in these water resources are within permissible bounds. The weathering of silicate and carbonate rocks primarily regulates their water chemistry. Zhang and associates (2017). High-altitude surface water resources, such as glacial-fed lakes, ponds, channels, etc., are the main sources of drinkable water for the local populace, tourists, hikers, and wildlife. Controlling the amount of water released by snowmelt in mountainous regions depends heavily on the hydrogeological and geomorphological systems (UNCSD, 2012).

Surface water resources come from rain, groundwater, or springs. However, water supplies located more than 3.5 km above mean sea level are considered glacial-fed, which means they can provide clean, fresh water devoid of dangerous contaminants (Kumar & Sharma, 2019).

Policymakers and water management authorities are able to control water pollution with the aid of ongoing monitoring and evaluation of water quality. The physical, chemical, and biological characteristics of the water are assessed (Wagh et al., 2019a). The water quality of these glacier-fed lakes reveals whether or not the water is suitable for human consumption (Vaux, 2001). Lakes found over 3500 meters are categorized as glacial lakes because they are thought to have developed as a result of glacier retreat (WWF 2005).

An effort was made to assess the water quality of Sato Panth Lake, a glacier lake located 4600 meters above sea level in Uttarakhand state, India's Garhwal Himalaya. Sixteen physio-chemical parameters related to temperature, alkalinity, hardness, conductivity, dissolved oxygen, pH, calcium, magnesium, chlorides, nitrates, sulphates, and phosphates were measured during the ice-free season in 2014 and 2015 between June and August. Free CO2 ranged from 8.40 to 8.60 mg L−1, total dissolved solids ranged from 88.0 to 89.5 mg, water temperature ranged from 0.1 to 0.3 °C, dissolved oxygen ranged from 5.90 to 6.0 mg, and mean pH values were between 6.85 and 7.10 L−1. Between 7.88 to 7.95 mg L−1 of calcium.

The range of magnesium levels was 0.53 to 0.66 mg/L-1. All of the physio-chemical results were below the WHO/BIS recommended level for drinking waters. The Water Quality Index (WQI), which was calculated using these data, further revealed the high quality of lake water. RC Sharma and associates (2017). In western North America, glaciers are an important natural resource and sensitive markers of climate change (Østrem, 1966; Meier, 1969). For example, British Columbia's (BC) glaciers alone make up around 3% of the continent (30 000 km2) and serve as frozen freshwater reservoirs that supplement precipitation and snowmelt flow in the summer and early fall. Glaciers provide a substantial amount of renewable energy in addition to sustaining ecological sustainability and the travel and tourism sectors in the US and Canada. The purpose of Meride et al. (2016)'s study is to examine the drinking water quality and how it affects the people living at Ethiopia's Wondo Genet Campus. Research was conducted to ascertain whether the drinking water in the study locations satisfied all physio-chemical standards in light of the findings.

WHO drinking water requirements were regularly met at every campus drinking water test location. A rock glacier affects the water that passes through it physically and chemically, acting as a concentrating mechanism rather than a filter. A model for the hydrological system of rock glaciers includes groundwater, avalanching ice and snow, runoff from adjacent slopes, direct precipitation, and initial glacial and/or periglacial ice. The primary outputs of the hydrological system include surface runoff, subsurface discharge, subsurface seepage, sublimation, and evaporation.

The surface, subsurface, groundwater, and cliff and talus subsystems comprise the cascade system. The model reveals many intricate pathways through a rock glacier, and the observed changes in water input and output quality need to be carefully considered. Since the nature of the inner features of rock glaciers must be predominantly defined by external data, the water leaving rock glacier systems was investigated. It was found that departing water had higher ion concentrations than incoming forms, and the total dissolved loads in the water input ranged from 1.5 to 6.0 mg l–The inputs' silica concentrations ranged from 0 to 0.1 mg l–1 to 1.9 to 6.0 mg l–1; the inputs' alkalinity values ranged from 1.3 to 2.7 mg l–1 CaCO3, while the outputs ranged from 18.1 to 44.4 mg l–1 CaCO3; and the inputs' total hardness values ranged from 0.0 mg l–1 CaCO3, while the outputs ranged from 21.0 to 50.1 mg l–1 CaCO3. Water flowing over three rock glaciers lost pH. The intakes and outputs into the rock glaciers had pH values between 6.4 and 7.0 and 7.2 and 8.5, respectively. The highest flow of the three rock glaciers occurred between 0900 and 1200 hours before the daily maximum temperature (JR Giardino, 2020). Three levels of drinking water safety were evaluated in the Bagh district, which was affected by the earthquake in Azad Jammu and Kashmir, Pakistan: sources, system, and residence. The thermo-tolerant fecal coliform, or Escherichia coli, was detected using the Oxfam-DelAgua portable water testing kit. We analyzed 254 samples of drinking water for the presence of fecal coliform.

The region's exposed drinking water sources, inadequate waste management, vulnerable sewage, and a lack of awareness about health and hygiene were shown to be the main causes of water contamination. (Ali and others, 2013). Rock glaciers (RGs) are a major supply of water for alpine regions under climate change. Recently, RG-fed streams have been shown to contain high concentrations of solutes, particularly trace elements, which negatively impacts the water quality. However, it is challenging to draw conclusions about the main mechanisms underlying solute export from RGs due to a lack of studies from a limited number of sites. Here, in an unprecedented effort, we collected published and unpublished data on the hydrochemistry of rock glaciers around the world. We investigated 201 RG springs from mountain ranges in North and South America, Europe, and other continents using a combination of machine learning, multivariate and univariate analysis, and geochemical modeling.

We found that 35% of springs coming from intact RGs (with internal ice) have water quality below drinking water standards, compared to 5% of springs associated with relict RGs (without internal ice). Ice and bedrock lithology interact to produce the solute concentrations in RG springs. Indeed, we found that water from intact RG springs contained more sulfate and trace elements than water from relict RGs, especially in specific lithological situations.

Increased sulfide oxidation is the reason for intact RGs' greater concentrations of trace elements. Water management issues may arise in mountain catchments that are abundant in intact RGs and where the underlying geology would make them geochemical RG hotspots. Our study represents the first comprehensive attempt to identify the main factors causing solute concentrations in RG waters. In 2024, S. Brighenti et al. The Snake-Columbia, Green-Colorado, and Wind-Missouri River systems all have headwaters in Wyoming's Wind River Range, which is home to more than 60 glaciers. The Continental Glacier, which covers an area of about 2.5 km2, is atop the northern Wind River Range. The Wind River and West Torrey Creek are fed by the meltwater from the Continental Glacier. Meltwater discharge from the upper Continental Glacier was measured in August 2012 and 2014. Water samples were collected in 2014 to examine stable isotopes, field properties, and 23 trace elements.

According to this study, continental glacier meltwater caused the mean flow of the Wind River above Red Creek to be 4.11 ± 18.38% in August 2012 and 2014, and the mean flow of Torrey Creek to be 32.91 ± 8.4%. By scaling these figures to all perennial snow and ice in the upper Torrey Creek basin, an estimate of 82.70 percent of Torrey Creek flow and 10.32 percent of Wind River flow above Red Creek during August was produced. Glacier meltwater contributions to Torrey Creek in relation to snow melt ranged from 81.05 to 82.70 percent of flow, with an average of 81.88 ± 1.17 percent for August 2014, according to δ18O ratios. In August 2014, 34.83% of the total phosphorus and 89.99 percent of the nitrate-nitrite

Meltwater from continental glaciers provided loading to Torrey Creek. The pH of the snow and glacier meltwater was lower than 6.0 due to nitrate-nitrite and other air deposits. Last but not least, trace element analysis showed distinct differences between water sources. (Kuldeep and others, 2023). On the Lagos State University campus, Ojo et al. (2016) conducted a study on the chemical and microbiological characterization of potable water. Four distinct locations were used for sampling, and the samples were then taken to the university lab for analysis. The outcomes match the recommended level. The findings demonstrated that although the water had high amounts of coliform, normal quantities of calcium, iron, and magnesium were present. It is therefore unsuitable for human consumption. The following A study found that the distribution system needed to be changed in order to lower microbial contamination.

According to Gad (2005), the complex ecology that may be found in both freshwater and marine habitats includes ponds, rivers, lakes, and estuaries. There may be thousands of species in the distinct biota of each of these settings. The frequent exposure of these biota, which include the flora and wildlife, to a range of toxicants, including those brought on by human activity, can occasionally lead to toxicity and environmental harm. Aquatic toxicology is the study of these harmful effects on marine and freshwater biota and the ecosystems that support them.

Since the industrial revolution in the late eighteenth century, new sources of pollution have been found virtually daily throughout the world, according to OMER (2019). Therefore, air and water pollution has the potential to according to (Canning & Death, 2019), anthropogenic stressors such as terrier enrichment, unration, industrial waste, deforestation, water abstraction, flood prevention engineering, sedimentation, climate change, and invasive species are putting freshwater ecosystems in jeopardy globally. If the health of the freshwater environment is to be maintained, effective management will require monitoring and evaluating change. Both biotic and abiotic factors are involved in maintaining an ecosystem's structure and function in the face of external stress. This chapter summarizes the main types of indicators that are commonly used to assess the condition of ecosystems.

According to OMER (2019), new causes of pollution have been discovered almost every day worldwide since the industrial revolution in the late eighteenth century. As a result, contamination of the air and water could occur anywhere. The rise in illnesses associated with the water serves as concrete evidence of the extent of environmental deterioration, but nothing is known about changes in contaminant rates. Four categories of water can be distinguished based on their quality. The physical, chemical, and biological characteristics that these four categories of water quality share are closely examined in order to study them. The high, glaciated Hindukush and Himalayan mountains, the plains and deserts of Punjab and Sindh, the mountain and semi-mountain ranges of Baluchistan, and the provinces of Khyber Pakhtunkhwa (KPK) are only a few examples of Pakistan's varied geology, topography, and climate (Khalid, 2017). Pakistan is physically separated into three parts, beginning with the highlands in the north, which include parts of Gilgit-Baltistan and Kashmir. The north is home to the Hindukush, Karakoram, and Pamir mountain ranges, as well as K2 and Nanga Parbat.The Indus River has tributaries that flow through the Indus Plain from Kashmir to the Arabian Sea. The Thar Desert is situated in the country's interior, between the Baluchistan Plateau in the west and the Cholistan Desert in Puga Province and the Rajasthan Desert in India. With a variety of climates ranging from tropical to temperate and desert in the coastal south, Pakistan is blessed to enjoy all four seasons. While the remainder of the country enjoys a monsoon season from July to September, with occasional variations in the plains of Punjab and Sindh, the northern and glaciated regions have extremely cold and snowy winters. As demonstrated by the current year of 2022, two extreme weather conditions—drought and flood—occur frequently each year. The main water supply is the Indus River System (IRS) (Pappas, 2011). Pakistan is getting closer to a water shortage, though, as the country's population, agricultural output, and other domestic demands have all increased.

Briscoe et al. (2005) assert that there is also an uneven distribution of readily available water for drinking, irrigation, and other uses. Pakistan is blessed with four distinct climates, year-round precipitation, and a geographic location that allows for a variety of temperature zones and rainfall. According to a World Bank estimate, Pakistan receives 200 mm of rain on average between July and September. (World Bank, 2021). Unfortunately, flooding and inadequate drainage and storage systems cause a large portion of the rainwater to wind up in the Arabian Sea. The research article's development took into account the Sustainable Development Goals (SDGs) and Millennium Development Goals (MDGs) of the United Nations, which deal with the provision of clean drinking water throughout Pakistan, water storage, management, and wise distribution, as well as the use of technology for wastewater recycling. This paper offers a thorough set of proposals to accomplish the SDGs by 2030 as a policy input to the pertinent government departments in Pakistan (Chaudhry G. M. 2007a).

The physicochemical characteristics of water were investigated by Smith et al. (2015). Total dissolved solids (TDS) levels were found to be higher than normal, which may be a sign of contamination. The taste and smell of the water can be impacted by high TDS levels, which raise concerns about its suitability for human consumption. Ahmad et al. (2019) looked at the presence of heavy metals in the water. Their results showed extremely high levels of lead, arsenic, and cadmium. Neurological abnormalities and organ damage are among the negative health effects of exposure to these heavy metals. This emphasizes how crucial it is to put into practice workable water management techniques to lessen heavy metal contamination.

According to (Ahmed et al.2012), the region is made up of snow-capped mountains, glaciers, and highlands. These snow-capped mountains are the source of rivers, lakes, waterfalls, and springs. The Himalayan and Karakoram mountains dominate the area. To the west is the "Hindu Kush" mountain range. It is home to several high mountain peaks, including Nanga Parbat, the queen of hills, and K2, the second-highest peak in the world. Gilgit-Baltistan is home to some of the longest glaciers in the world outside of the Polar Regions, including as the Biafo, Baltoro, Batura, Saltoro, Rimo, Terung, Hispar, ChogoLungma, and Panmah Karakoram range. In the winter, these mountains receive a lot of snow, and in the summer, streams of water run down the hills as the snow and glaciers melt.

3. Research Methods and Materials

3.1. Study area

This study was conducted in Sumayar Valley, Nagar District, Gilgit–Baltistan, a high-mountain setting where the Karakoram, Himalaya, and Hindu Kush ranges intersect. Elevations increase from approximately 2,000 m at the northern entrance to more than 7,200 m near Diran Peak. Glacial meltwaters feed the Mamubar Stream and ultimately converge with the Hunza–Nagar river system. Settlements and small irrigation channels line the valley floor, while active gemstone mining occurs on steep slopes above central Sumayar.

Figure 1: Study area

3.2. Geographical and Mining Context

Surface hydrology comprises upper glacial tributaries, mid-valley channels, and lower community supply canals. The Chumar Bakhoor pegmatite field lies above 4,000 m and is seasonally worked from mid-July to mid-October. Waste rock and adits are proximal to snowmelt channels, creating potential pathways for suspended solids and dissolved ions to enter surface waters.

3.3. Research Design

A stratified transect was established to isolate three hydrological strata: glacier-proximal sources, mining-affected flows, and downstream community channels. The design captures longitudinal changes in water quality along a glacier–mine–community continuum during the active mining period.

3.4. Sampling Sites and Schedule

Sampling took place on 9 September 2024. Within each stratum, three spatially independent sites were selected, yielding nine grab samples in total. Water was collected into clean 500 mL bottles, stored cool and dark, and transported the same day for analysis. Field metadata included date, time, GPS location, and site notes on flow conditions and visible turbidity.

3.5. Field Measurements and Sample Handling

In situ measurements of pH, electrical conductivity, total dissolved solids, temperature, and turbidity were obtained using calibrated handheld meters. Bottles were rinsed with sample water prior to filling and were capped without headspace where feasible. Chain-of-custody documentation tracked sample handling from collection through laboratory receipt.

3.6. Laboratory Analyses

Salinity was derived from conductivity according to instrument algorithms. Total hardness as $CaCO_3$ was determined by standard titrimetric methods. Chloride was quantified by argentometric or colorimetric procedures appropriate to the concentration range. Nitrite was measured by diazotization colorimetry. Analytical reporting limits and calibration ranges were recorded in laboratory logs.

3.7. Quality Assurance and Quality Control

Meters were calibrated daily with traceable standards. One field duplicate per stratum and at least one field blank were collected. Acceptance criteria included instrument drift within manufacturer tolerances, duplicate relative percent difference within fifteen percent for laboratory analytes, and blank results below reporting limits.

3.8. Data Analysis and Compliance Benchmarking

Descriptive statistics were computed by stratum and across all sites. Where distributional assumptions were met, one-way analysis of variance was applied to compare strata; otherwise, non-parametric tests were used. Observed concentrations were interpreted against World Health Organization, Pakistan Standards and Quality Control Authority, and National Environmental Quality Standards guideline values to assess suitability for drinking and domestic use.

4. Results

4.2. Physical Parameters

Across nine samples along the glacier to mine to community transect, water appeared fair at a distance but was non-transparent at close range in mining reaches. Taste and odor were not discerned in any stratum. These sensory observations align with Pakistan's National Standards for Drinking Water Quality, which require color below fifteen true color units and "non-objectionable" taste and odor for acceptability.

4.2. Electrical Conductivity

Conductivity was lowest at the glacier source (156–158 $\mu S\ cm^{-1}$) as shown in Figure 2, extremely elevated in mining flows (1,577–1,579 $\mu S\ cm^{-1}$), and intermediate in community channels (381–383 $\mu S\ cm^{-1}$), yielding a cross-site mean of 705.67 $\mu S\ cm^{-1}$. Because electrical conductivity is a proxy for ionic strength and covaries with total dissolved solids, the mining peak indicates pronounced solute enrichment at the point of disturbance, World Health Organization. Although no health-based EC guideline exists, the associated rise in dissolved salts has implications for taste and scaling.

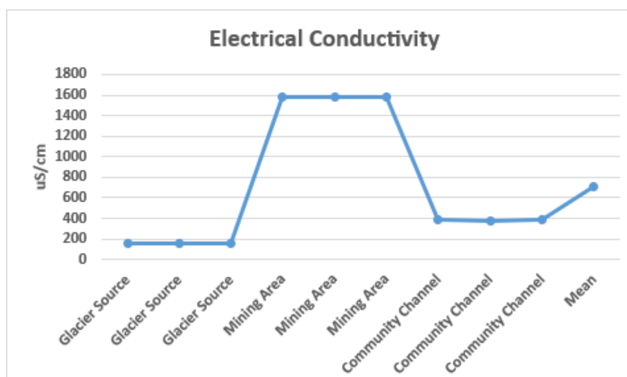

Figure 2: Electrical conductivity across glacier, mining, and community sites with overall mean (μS/cm)

4.3. pH

pH remained near neutral to slightly alkaline across all sites (overall mean 7.40), see figure 3, within the customary 6.5 to 8.5 operating range used for distribution system stability and consumer acceptability WHO.

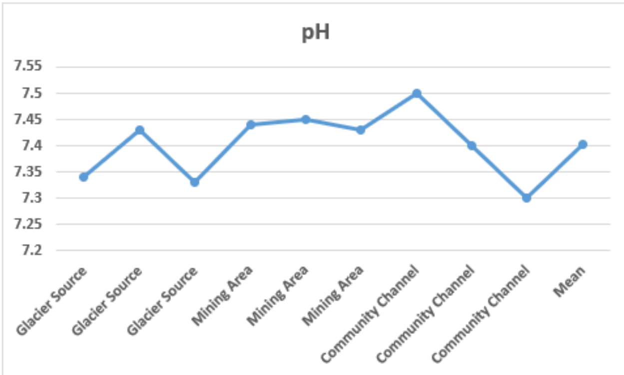

Figure 3: pH across glacier, mining, and community sites with overall mean

4.4. Total Dissolved Solids and Salinity

Total dissolved solids tracked the conductivity pattern, with glacier water at 77.2–77.4 mg L^{-1}, mining flows at 564–566 mg L^{-1}, and community channels near 191–193 mg L^{-1} (overall mean 278.10 mg L^{-1}) see figure 4. By WHO palatability guidance, water under 300 mg L^{-1} is generally rated "excellent," 300–600 "good," and 600–900 "fair," which explains why community and glacier waters were acceptable while mining waters approached the threshold at which taste can deteriorate.

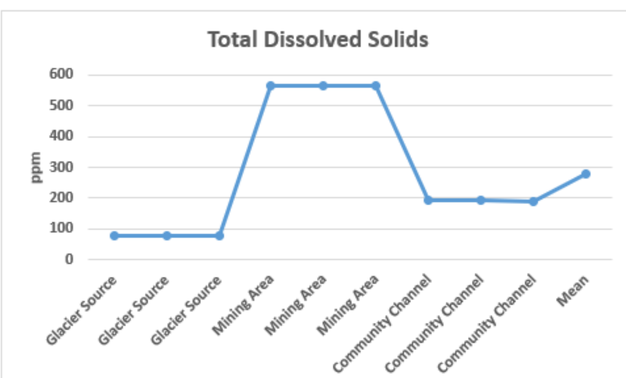

Figure 4: Total dissolved solids by site with overall mean (mg L^{-1})

4.5. Turbidity

Turbidity exhibited the strongest mining signal. Glacier values were 87.7–87.9 NTU, mining values 307–309 NTU, and community values 63.7–63.9 NTU (overall mean 153.2 NTU) see figure 5. These levels substantially exceed both Pakistan's target of less than five NTU and the WHO operational target of less than one NTU before disinfection because turbidity interferes with pathogen control. The magnitude of turbidity at the mine is consistent with fine-sediment mobilization from high-gradient works, which is known to elevate suspended loads in mountain streams and degrade benthic habitats (Bylak & Kukuła, 2022).

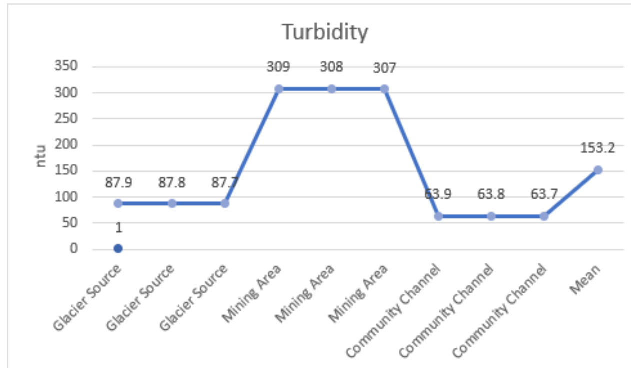

Figure 5: Turbidity by site with overall mean (NTU)

4.5. Salinity

Salinity increased at the mine and partially attenuated downstream. Glacier samples were 112.5, 112.4, and 112.3 mg/L; mining samples were 980, 979, and 978 mg/L; community samples were 137, 136, and 135 mg/L. The mean across all sites was 409.13 mg/L see figure 6.

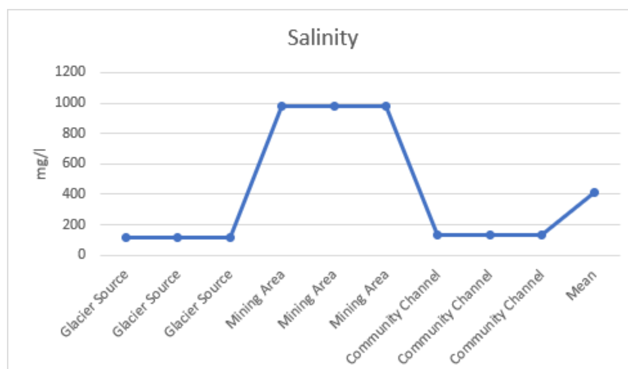

Figure 6: Salinity by site with overall mean (mg L^{-1})

4.6. Chloride, Nitrite, and Hardness

Chloride was low throughout (means near one to three milligrams per litre), consistent with the absence of saline sources see Figure 7. Nitrite rose in mining flows to 0.6–0.7 mg L^{-1} see Figure 8 but remained near detection at glacier and community sites. These nitrite values are below the WHO guideline of three milligrams per litre as nitrite ion, although management should aim for as-low-as-reasonably-achievable concentrations given potential infant risks. Total hardness as calcium carbonate was uniformly very low at approximately 2.5–2.7 mg L^{-1}, see figure 9, classifying all waters as soft and indicating negligible carbonate weathering along the transect U.S. Geological Survey.

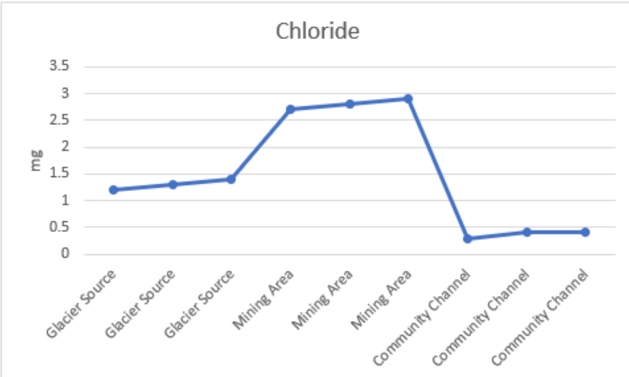

Figure 7: Mean value of chloride

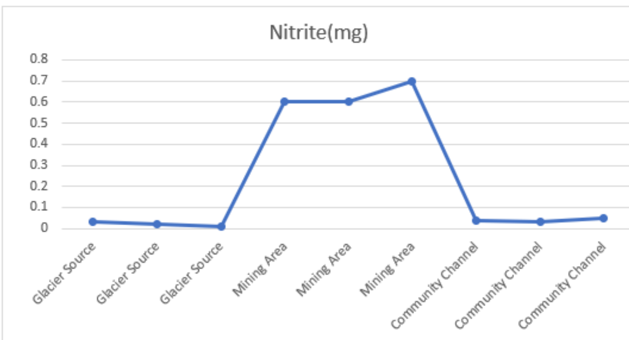

Figure 8: Mean value of nitrite

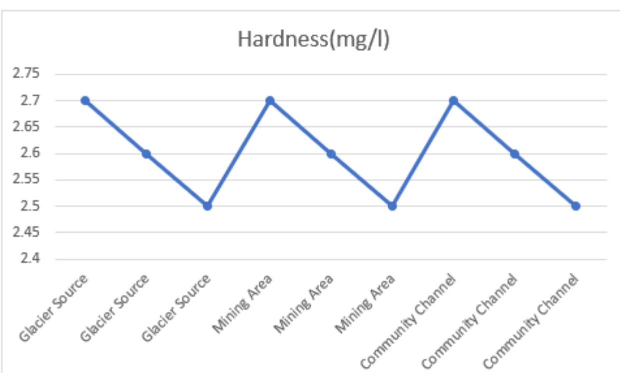

Figure 9: Mean value of hardness

5. Discussion and Conclusion

The parameter suite exhibits a coherent hydrological signal along the glacier–mine–community transect. Electrical conductivity, total dissolved solids, salinity, turbidity, and nitrite reach maxima at the mining locus and decline downstream, whereas pH remains stable within the customary operating range and chloride and total hardness remain low. The very high turbidity measured at the mine is the most immediate impediment to potability because it interferes with disinfection efficacy and diminishes aesthetic quality. Such turbidity is consistent with direct sediment entrainment from adits, spoil heaps, and steep access paths. Parallel increases in conductivity and total dissolved solids indicate enhanced ionic export from freshly exposed pegmatitic materials and disturbed soils. The partial attenuation observed in community channels reflects dilution and settling rather than full removal, which means that relying on natural self-purification cannot ensure a robust margin of safety for domestic use. Persistently very low hardness across all strata implies limited buffering capacity and raises a secondary operational concern: without careful control of pH and disinfectant residuals, distribution systems supplied by these waters may face an elevated risk of corrosion. Taken together, the results align with broader evidence that mineral extraction in high-relief catchments intensifies particulate and dissolved loads to receiving waters and therefore requires both source controls at the works and treatment prior to consumption World Health Organization (2017).

High-elevation gemstone extraction in steep terrain can swiftly transmit suspended solids and solutes from disturbed slopes into headwater channels with direct consequences for household water safety. The stratified assessment in Sumayar Nagar isolates the mining contribution from glacial sources and community supplies and shows a consistent pattern: conductivity, total dissolved solids, salinity, turbidity, and nitrite peak at the mine and decrease downstream; pH remains acceptable; chloride and hardness stay low. Conductivity near 1,580 µS cm^{-1} and total dissolved solids around 565 mg L^{-1} at the mine document pronounced ionic enrichment, while turbidity above 300 NTU constitutes an immediate barrier to safe drinking water. Although nitrite remains below health-based guideline values, localized elevations near the workings warrant control and continued surveillance. The study's principal significance is the delivery of a defensible baseline for a remote, data-poor setting using a design that separates source waters from mining-affected flows and applies explicit quality assurance. The evidence directly supports targeted mitigation at adits and spoil piles and specifies the need for clarification and filtration before disinfection for any abstraction influenced by mining activities. Limitations include the single-day sampling window during active operations, the focus on core physicochemical indicators, and the derivation of salinity from conductivity rather than full ionic balance. These constraints do not alter the central inference that mining is the dominant driver of the observed deterioration; rather, they identify efficient directions for strengthening management, including seasonal replication across the mining window, expansion to metals and metalloids characteristic of pegmatitic lithologies, and concurrent microbiological testing when turbidity is elevated. Overall, the findings support immediate operational responses and a structured monitoring plan that links site-scale controls to community-level drinking-water protection.

6. Recommendations

- Install source controls at mine workings, including sediment traps, check dams, and lined settling ponds sized to local storm intensity, and stabilize spoil piles with grading, surface armoring, and vegetation.
- Require clarification and filtration before disinfection for any water abstracted from mining-affected channels, with continuous turbidity targets consistent with effective microbial inactivation.
- Establish a seasonal monitoring program that includes turbidity, suspended solids, major ions, nitrite and nitrate, trace metals relevant to local pegmatites, and microbial indicators at glacier, mine, and community strata.
- Implement near-real-time sensors for conductivity and turbidity at sentinel sites, coupled with automatic samplers during runoff events to capture short-duration peaks.
- Develop a water safety plan for Sumayar communities that defines trigger values, operational responses, and public communication protocols during high-turbidity periods.
- Pilot low-cost nature-based measures along access paths and drainage lines, such as vegetated swales and coir-log check structures, to reduce fine sediment transport from steep slopes.
- Introduce training and compliance audits for mining crews on waste handling, fuel storage, and greywater management to reduce nutrient and microbial inputs near channels.
- Coordinate with district authorities to align mine permitting with hydrological risk screening, including setback distances from flow paths and requirements for progressive reclamation.

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