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Review Article

Temporal changes in water quality in Leh Ladakh region: Impact of urbanization

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ABSTRACT

Water is a valuable and limited resource in semi-arid regions like Ladakh. Effective management and conservation of water are crucial to prevent negative consequences on the area's quality of life. Since becoming a Union territory, Leh, a district of Ladakh, has undergone rapid urbanization due to its administrative status, air service facilities, tourism, and increasing population. However, this urbanization and tourism boom have resulted in a higher demand for water and a decline in its quality. Glacial-fed water is the primary source for drinking and agriculture in Ladakh. As Ladakh has become a popular tourist destination, the distribution and quality of water have been negatively affected. Construction of hotels and guest houses on agricultural lands, could further harm Ladakh's fragile ecological environment. Due to the challenging terrain and harsh conditions, there has been limited research on water quality in the region andare confined to the Leh district only. Despite lack of comprehensive information, this review aims to address three important questions: the hydrochemistry of water resources, the impact of urbanization on water quality, and the existing research gap in hydrochemistry in significant areas and water resources. The objective is to establish fundamental data for future research and contribute to a better understanding of water resources in the region.

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INTRODUCTION

According to the World Cities Report 2022 by the United Nations-Habitat [1], India's urban population is projected to reach 675 million by 2035, making it the second-largest urban population after China, which is expected to have one billion urban dwellers. The report highlights that urbanization is a prominent trend in the 21st century, with an estimated 43.2% of India's population residing in urban areas by 2035. The growth paths of major economies like China and India have a significant impact on global inequality, given their large population shares. While high-income nations differ in their urbanization rates and growth rates, the study emphasizes the crucial role of cities in shaping the future of humanity [1, 2]. As population growth, industrialization, urbanization, and economic development progress, water consumption and contamination of water bodies increase significantly. The paper notes that anthropogenic activities such as industrial and sewage waste contribute to severe pollution of water bodies [3].

Despite the crucial role of fresh water in supporting life, a significant portion of the Indian population consumes water that is contaminated. This has severe consequences, with over two million people dying due to polluted water. The

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degradation of drinking water quality is becoming increasingly evident in tourist destinations like Manali, a small town in Himachal Pradesh, as urbanization and tourism grow [4]. Similarly, South Asian countries are experiencing a decline in water quality due to unregulated urbanization, improper disposal of industrial and municipal waste, and inadequate filtration and disinfection practices. These factors contribute to the contamination of both surface and groundwater [5, 6]. Urbanization is not limited to lowland areas alone; it affects various regions, including mountainous areas such as Ladakh. The challenges faced in these areas include limited resources, difficulties in accessibility, and heightened vulnerability to population changes [7].

Anthropogenic activities in river basins have disrupted the self-purification capacity of rivers, leading to the degradation of this vital ecosystem. Surface water bodies are particularly susceptible to contamination due to the ease of discharging effluents into them [8]. This is especially true in arid and semi-arid regions where groundwater plays a crucial role in meeting drinking, residential, agricultural, and industrial needs. The contamination of groundwater by heavy metals poses a significant threat, even at low concentrations [9]. Climate change has both direct and indirect consequences on water resources, agriculture, and livelihoods, exacerbating the challenges. Increasing water demand from cities, businesses, and agriculture, along with rising pollution levels, seasonal water shortages, and floods, worsens the situation [10]. In areas such as Cameron Highlands, Malaysia, the water quality of rivers, including Bertam River, has been negatively impacted by the surge in construction, tourism-related activities, and farming [11]. Given the current trends of urbanization and tourism growth, it is imperative to adopt sustainable approaches to water supply to preserve the natural quality of water and ensure a sustainable future.

Ladakh, consisting of Leh and Kargil districts, became a separate union territory in India on October 31, 2019, following the Jammu and Kashmir Reorganisation Act, 2019. Since then, Leh district has experienced rapid urbanization due to the presence of administrative offices and a civilian airport. A study has highlighted the role of the army and tourism in the floating population as a significant factor contributing to urbanization in Ladakh [12, 13]. This shift from agriculture to a tourism-based economy in Leh has resulted in unequal access to water resources, causing detrimental social and environmental changes that have negatively impacted the quality and availability of water [14]. This urbanization trend in Ladakh bears similarities to a study conducted in China by Qian and co-workers [15], emphasizing the impact of tourism-driven urbanization. This study centers on the Leh Ladakh region of India, aiming to investigate various distinctive challenges such as rapid urbanization, the unique climate and water scarcity, the surge in tourism, and the transition from an agricultural to a tourism-based economy. These challenges are particularly unique to this region in contrast to other parts of the country. Additionally, the study seeks to offer insights into more sustainable water management practices and pollution control measures. In the past, the residents of Ladakh used to build their homes on unsuitable soil used for farming, while utilizing areas with high groundwater levels for agriculture. However, there has been a significant shift in this trend recently. Agricultural and barren fields are now being converted into private housing or tourist infrastructure, erasing the distinction between cultivated and inhabited land. As a result, the reliance on traditional surface water systems for everyday use has been replaced by groundwater as the primary water source [14].

Despite the dearth of comprehensive data on the hydrochemistry of water resources in Leh, Ladakh, this review article endeavours to tackle several critical inquiries:

i. Explore Existing Research: Explorethe existing research conducted on hydrochemistry and related fields in the region, to provide a comprehensive understanding of the current state of knowledge.

ii. Assess Tourism-driven Urbanization Impact: Analyse the ramifications of tourism-driven urbanization on water quality in the region, shedding light on potential challenges and identifying areas for improvement.

iii. Anticipate Future Consequences: Forecast future consequences by drawing parallels with similar semi-arid areas where water quality issues are already prevalent, offering insights into potential trajectories and outcomes for Ladakh.

iv. Advocacy towards Sustainable Planning: Sensitize policymakers to the urgent need for sustainable future planning, emphasizing the importance of proactive measures to safeguard water resources and mitigate adverse effects of urbanization and tourism.

v. Identify Research Gaps: Identify and address research gaps in hydrochemistry pertaining to significant locations and water sources in Ladakh, facilitating targeted investigations and informed decision-making.

vi. Establish Baseline Data: Establish baseline data to serve as a foundation for future investigations into water quality and hydrochemistry in the region, enabling ongoing monitoring and assessment of environmental conditions.

By pursuing these objectives, this review aims to contribute to a deeper understanding of the hydrochemical dynamics in Leh, Ladakh, and suggest for sustainable practices to ensure the preservation and responsible management of water resources for future generations.

BRIEF ABOUT THE STUDY AREA

Ladakh, situated in the northernmost part of the trans-Himalaya region, is recognized as one of India's largest cold deserts. Its geographical coordinates lie between 31°44′57″ and 32°59′57″N latitude and 76°46′29″ and 78°41′34″E longitude (Fig. 1). The area falls under the rain shadow of the Greater Himalayas, shielding it from the influence of the southwest monsoon. Instead, it experiences the impact of

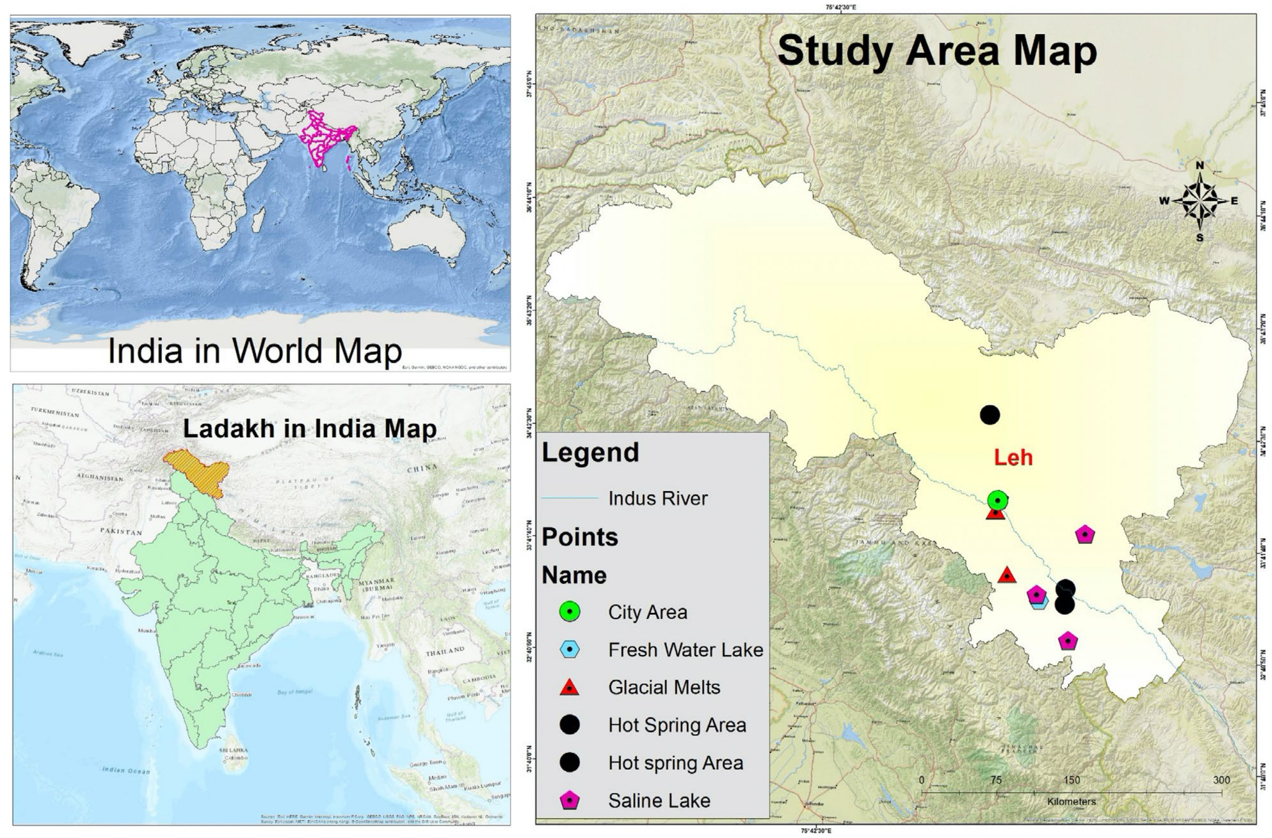


Figure 1. Study area map of Leh Ladakh region.

westerly winds [16, 17]. The region is characterized by extremely cold temperatures caused by the prevailing Arctic winds throughout most of the year, resulting in a distinctive climate characterized by extreme dryness. Ladakh receives low annual precipitation, with only 20–30 mm of rainfall or snowfall. It also has prolonged sub-zero temperatures, ranging from -30 °C to -75 °C in different areas. The terrain is rugged and challenging, and the humidity remains low, ranging from 20% to 40%. These conditions make Ladakh a semi-arid cold region [18, 19]. Despite these harsh conditions, Ladakh is rich in natural features such as high-altitude lakes, glaciers, streams originating from melting glaciers, barren mountains, steep gorges, hot springs, and rivers [18, 20]. The region's cultural diversity adds to its appeal, attracting trekkers, tourists, and researchers. The streams, rivers, springs, and groundwater, fed by glacial and snowmelt sources, are crucial sources of water for the population living in glacial-fluvial moraines, large scree deposits along foothills, and active mega alluvial fans within river valleys [21].

GEOLOGY OF LADAKH

The Ladakh Himalaya consists of five geotectonic units arranged in a north-to-south sequence [22]. These units are the Karakoram block, Shyok suture zone, Ladakh arc, Indus suture zone, and Tethys Himalayas (Fig. 2).The Karakoram block is a region characterized by a diverse range of rocks that span from the Late Precambrian to the Cretaceous period. Within this zone, there are metamorphic, igneous, and sedimentary rock types that were formed between the Permo-Carboniferous and Late Cretaceous periods. The metamorphic rocks found here consist of schists, quartzites, augen gneisses, and migmatites. The igneous rocks include granites, granodiorites, and tonalities, collectively known as the Karakoram Batholith. The sedimentary rocks present in this region encompass limestones, dolomites, shales, sandstones, as well as small occurrences of conglomerate lenses [23].

The Shyok suture zone, which separates the Ladakh arc from the Karakoram block, consists of mafic-ultramafic rocks, sedimentary rocks, and metamorphic rocks. Within the Shyok formation, there are two sections known as the lower and upper members. The lower member is primarily made up of sandstone, conglomerate, and some limestone, while the upper member is comprised of volcaniclastic rocks [22]. The Ladakh arc, which is part of the Trans-Himalayas, is a geological formation resulting from the movement of the Neo-Tethys oceanic plate beneath the Eurasian landmass. It comprises of batholithic, rhyolitic, and andesitic rocks. Spanning approximately 600 km in length and 30–80 km in width, the Ladakh arc is a substantial component of the Trans-Himalayas [24].

The Indus Suture Zone (ISZ) is a region where various geological units are juxtaposed from south to north. These units include the Lamayuru Complex, which is

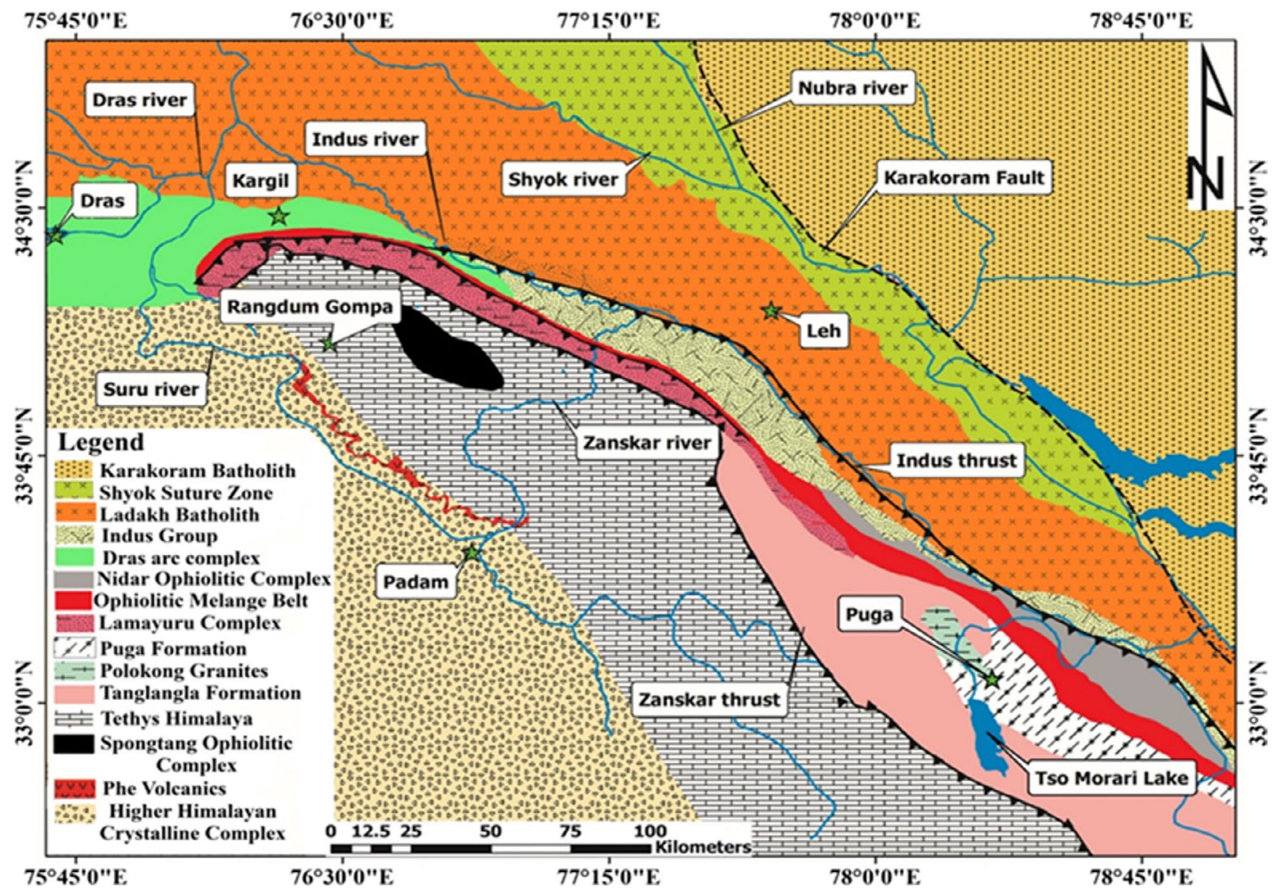


Figure 2. Geological map of the Ladakh Himalaya showing various tectonostratigraphic units. Reproduced with permission from Ref. [25], Copyright (2023) from Springer.

Note: The blue line (–––) Rivers and the black broken line (- - - -) signifies fault.

a deposit formed on a continental slope, an ophiolitic melange belt, the Dras arc complex representing an island arc formed within an ocean, remnants of the Neo-Tethys Ocean in the form of ophiolitic relics, the Indus Group consisting of molassic deposits, and the Ladakh Batholith, which is a plutonic complex. The age of these units spans from the Late Permian to the Eocene period [25].The Tethys Himalayas consist predominantly of fossil-rich sedimentary deposits that were formed between the Precambrian and Cretaceous periods along the northern edge of the Indian subcontinent. The northern section of this mountain range has undergone metamorphism at extremely high pressures [22].

HYDROCHEMISTRY OF WATER RESOURCES IN LADAKH

The Hindu Kush-Himalayan region is often referred to as the "Third Pole" due to its vast freshwater reserves, second only to the polar regions. These reserves exist in the form of glaciers, lakes, rivers, ponds, and springs, and are closely tied to the region's climate. The Ladakh region, an integral part of the Himalayas, relies primarily on precipitation, particularly snowfall in winter, as its main water source. As snow and ice melt during winter and early spring, they contribute to the sustained flow of perennial rivers downstream. These meltwaters, originating from glaciers and high-altitude snow, play a crucial role in the Indus River's flow, replenishing groundwater reserves, and nourishing alpine lakes [26].

Meltwater Chemistry

Glacier melts have traditionally been considered a clean source of water, but as temperatures rise, the interaction between water and rocks intensifies. This leads to the water becoming heavily contaminated with sediment and dissolved substances as it flows through channels within and beneath the glacier [27, 28]. The chemical composition of the water is also affected by various factors, such as the formation of basal ice layers during the winter, biological processes, cation exchange, mineral weathering, and ion separation during thawing and percolation through the snowpack [29, 30]. As a result, the meltwater becomes enriched with ions such as Ca^{2+}, Mg^{2+} and K^+ compared to the original snow [30, 31]. Human activities associated with increased urbanization and tourism have further contributed to the deterioration of water quality in these areas [3].

The previous studies conducted in the area, as summarized in Table 1, indicate that the concentration of ions in glacial melts follows the order $Ca^{2+} >> Mg^{2+} > Na^+ > K^+$ and HCO_3^-

Table 1. Physicochemical parameters of glacial melts of Leh Ladakh

Source ID	Sampling period	pH	Na	K	Ca	Mg	HCO_3	SO_4	NO_3	Cl	TDS	F	Si	Ref
UG_GM_2010_EMP	Early melt period 2010	5.2–7.3	22.20–55.50	6.82–25.54	67.35–391	25.83–72.83	110–440	37.96–61.90	0.16–2.26	8.18–14.10				[30]
UG_GM_2010_EMP	Early melt period 2010	6.60	33.93	12.84	228.00	42.07	253.00	47.52	0.83	10.98				
UG_GM_2010_PMP	Peak melt period 2010	5.3–7.0	17.60–37.0	3.69–19.87	94.45–243	24.08–59.08	80–290	0.44–4.36	41.73–60.94	6.21–13.26				
UG_GM_2010_PMP	Peak melt period 2010	6.20	26.15	8.16	157.00	36.95	170.00	1.36	49.73	10.43				
UG_GM_2010_LMP	Late melt period 2010	6.4–7.2	33.40–127.10	9.69–14.97	190–1159	49.33–282	200–1450	0.09–2.68	41.25–62.27	0.65–1.45				
UG_GM_2010_LMP	Late melt period 2010	6.60	50.99	11.73	387.00	82.25	452.00	0.91	48.91	1.04				
LT_GM_2019_S	Summer 2019	7.30–8.30	34.0–81.0	0.56–1.17	6.64–24.86	0.95–3.28	18.30–42.70	3.91–16.54	1.37–2.36	0.13–1.72	32.4–91.95	0.06–0.13	0.38–0.76	[98]
LT_GM_2019_S	Summer 2019	7.83	54.20	0.72	11.88	1.73	31.11	5.38	1.73	0.51	57.29	0.72	0.56	
SK_GM_2019_S	Summer 2019	7.30–8.40	34.0–81.0	0.41–0.66	12.30–30.90	0.81–2.36	26.80–67.10	3.80–16.13	0.93–2.80	0.57–0.18	41.0–103.0	0.03–0.11	0.42–0.86	
SK_GM_2019_S	Summer 2019	7.96	72.30	0.52	24.27	1.47	53.92	10.15	1.70	0.39	94.90	0.06	0.62	
CN_GM_2019_S	Summer 2019	8.30–8.50	103.0–119.0	0.97–1.19	39.01–32.98	5.15–6.28	67.10–88.10	23.82–27.89	1.50–2.10	0.75–1.56	132.48–160.15	0.08–0.13	1.02–1.30	
CN_GM_2019_S	Summer 2019	8.36	112.40	1.08	31.11	5.81	73.74	26.70	1.72	1.00	145.00	0.10	0.11	
LT_GM_2018_S	Summer 2018	7.40–8.20	29.0–34.60	0.66–3.95	5.47–12.34	0.49–1.72	24.40–36.60	1.17–5.79	044–2.52	1.66–4.85	36.50–67.95	0.04–0.39	0.40–0.70	
LT_GM_2018_S	Summer 2018	7.77	47.27	2.16	9.60	1.39	31.52	4.11	1.28	2.71	54.85	0.16	0.53	
SK_GM_2018_S	Summer 2018	7.60–8.30	31.10–74.20	7.26–12.98	0.57–3.78	0.46–3.46	18.30–91.50	0.80–12.78	1.12–2.10	1.05–2.26	30.51–119.26	0.02–0.08	0.50–0.85	
SK_GM_2018_S	Summer 2018	7.95	52.33	11.35	2.05	2.04	66.49	5.53	1.47	1.62	93.46	0.05	0.73	
CN_GM_2018_S	Summer 2018	8.0–8.3	102.1–117.0	1.19–2.10	16.45–29.14	2.90–3.80	73.20–105.90	12.43–14.55	0.74–1.70	1.47–1.99	118.22–146.12	0.02–0.10	0.93–1.20	
CN_GM_2018_S	Summer 2018	8.13	108.15	1.75	20.31	3.20	85.23	13.23	1.33	1.74	129.75	0.08	1.05	

UG_GM: Upper Ganglass Glacial Melt; LT_GM: Lato Glacial Melt; SK_GM: Stok Glacial Melt; CN_GM: Chabe Nama Glacial Melt. S and W along with the years indicate sampling periods in summer and winter respectively. EMP, PMP, and LMP along with the years indicate sampling periods in the early, peak, and late melting periods respectively. The concentration of ions for the Upper Ganglass Catchment is in μeq/L, EC in μS/cm, and the remaining parameters are in mg/L.

>> SO_4^{2-} > Cl^- > NO_3^-> PO_4^-. This suggests that carbonate rock weathering plays a significant role in determining the chemistry of these melts. Additionally, the studies report a substantial contribution from calcite rocks, sulphide oxidation coupled with silicate weathering, ion exchange processes, and atmospheric deposition (such as alkaline dust, anthropogenic pollutants, and sea salt aerosol). These factors are further intensified by physical weathering in steep slopes [32].The high ratio of Ca^{+2}/Mg^{+2} (>4) and the dominance of Ca^{+2} over Na^+ also support the influence of carbonate rock weathering. Another study revealed that during the peak melt period, there is minimal residence time and interaction with the water surface, resulting in a relative decrease in solute content in the water [30].

River water (Indus)

The Himalayan glaciers play a crucial role as water reservoirs, supplying mountain rivers with water throughout the year [33–35]. In Ladakh, India, the Indus River is a significant source of drinking water and irrigation. Its origin lies in China, and it passes through Ladakh before reaching India [19, 36, 37]. Approximately 70% of the water in the Indus River comes from glaciers and heavy snowfall [19, 38, 39]. Previous studies, summarized in Table 2–4, indicate that the concentration of major ions in the Indus water basin generally follows the order, Ca^{2+} >> Mg^{2+} > Na^+ > K^+, HCO_3^- >> SO_4^{2-} >Cl^-. These studies also explain that Ca^{2+} and Mg^{2+} primarily result from the weathering of carbonate rocks, gypsum, or anhydrite, while Na^+ and K^+ originate from silicate rocks and numerous salt lakes present in the basin [19, 25, 26, 38–40]. Isotopic data and the Ca^{2+} + Mg^{2+}/Na^+ + K^+ ratio, which is almost three times the world average of 2.2, further confirm that weathering of carbonate lithology is the main factor influencing the chemistry of major ions. The concentration of silicate in the Indus water averages around 6 ppm, like other high-altitude rivers that drain from the Himalayas. However, in the lower-lying areas of the Indus, this value increases to 19 ppm, indicating a higher rate of chemical weathering in these regions compared to the highland areas where mechanical weathering is predominant. The Suru River, one of the tributaries of the Indus River, exhibits the highest reported rate of carbonate weathering due to its steep average catchment slope [19].

The information available in the literature highlights several key points about the composition and characteristics of the Indus River [19, 40–44].

i. Anions: The bicarbonate ions in the Indus River come from the weathering of carbonate rocks (~75%) and silicate rocks (~25%). The presence of SO_4^{2-} is attributed to the weathering of gypsum, while Cl^- originates from halite deposits.

ii. Weathering Processes: The weathering of gypsum by H_2SO_4 is explained by the higher concentration of SO_4^{2-} ions compared to Cl^- ions. Hot springs along the riverbank have high sulphur content which supports this weathering process. Additionally, the dissolution of at-

Table 2. Concentration of major ions (mg/L) in the Indus River, Leh Ladakh

Source ID	Sampling period	Value	Parameters												Ref
			HCO_3	Ca	Mg	Na	K	F	Cl	NO_3	SO_4	PO_4	CO_3	TOC	
IR_1991_S	Summar-1991	Range	78.6–104.3	20.9–24.2	4.6–5.5	3.4–13.3	1.0–1.6	0.1–0.3	1.8–8.6	0.9–9.3	12.3–29.0				[39]
IR_1991_S	Summar-1991	Mean	91.3	22.3	5	9.9	1.4		6.4	1.7	16.7				
IR_1996_S	Summar-1996	Range	67–107	18–28.8	1.5–7.1	5.6–9.4	1.7–1.9	0.12–0.57	3.3–7.3	0.10–0.17	9.2–21.4				[63]
IR_1996_S	Summar-1996	Mean	81.2	24	4.5	7.3	1.6	0.3	4.8	0.12	11.9				
IR_2009-10_S	Summar-2009-10	Range	14.04–30.60	61.68–73.81	29.28–33.86	60.19–62.53	30.20–31.42	0.02–0.47	12.81–27.63	0.02–0.09	0.36–4.84	0.09–1.94	0.00–6.88	0.40–7.30	[65]
IR_2009-10_S	Summar-2009-10	Mean	23.46	88.33	31.18	60.98	30.6	0.2	23.48	0.04	3.92	0.35	2.99	1.07	
IR_2009-10_W	Winter-2009-10	Range	11.84–28.40	63.76–84.62	29.69–35.90	60.56–64.66	30.54–33.18	0.2–0.7	10.32–28.23	0.1–3.4	2.00–6.48	0.01–1.86	0.19–6.43	0.25–7.15	
IR_2009-10_W	Winter-2009-10	Mean	21.26	66.99	31.49	62.16	31.63	0.4	20.44	1.5	2.28	0.27	2.55	0.92	
IR_2011_S	Summar-2011	Range	82.2–140.6	17.0–38.1	4.9–7.7	2.7–14.5	1.1–2.0		1.4–10.1	0.0–0.2	12.7–32.9				[99]
IR_2011_S	Summar-2011	Mean	107.1	27.3	6.2	8.1	1.5		4.6	0.1	21.7				
IR_2013_S	Winter-2013	Range		31.09–52.99	5.05–6.3	10.81–79.53	0.3–114.3	0.31–0.20	16.1–30.0	1.34–0.45	43.7–72.30	ND			[97]
IR_2013_W	Winter-2013	Mean		41.66	5.78	50.3	62.6	0.24	24.9	0.86	57.7				
IR_2019_S	Summar-2019	Range	97.60–80.60	32.27–26.50	7.61–6.64	15.87–10.56	2.59–1.87	0.26–0.11	6.82–4.22	0.89–0.58	27.34–21.45				[98]
IR_2019_S	Summar-2019	Mean	87.17	27.86	7.07	13.73	2.1	0.21	5.34	0.8	23.39				
IR_2018_S	Summar-2018	Range	118.0–107.0	23.0–19.0	5.60–4.30	6.55–2.30	2.50–1.90		7.01–3.26	1	24.0–18.47				
IR_2018_S	Summar-2018	Mean	110.93	21.4	4.95	5.29	2.13		6.11		20.2				
GM*		Mean	58.4	15	4.1	2.3	6.3		7.8		11.2				[61, 99]

*Global Mean of Some Major Rivers of the World. IR: Indus River: S and W along with the years indicates sampling period in summer and winter, respectively; ND: Not detected.

Table 3. Physicochemical and biological parameters of Indus River, in Leh Ladakh

Source ID	Parameters													Ref
	DO (mg/L)	Free CO_2 (mg/L)	Alkalinity (mg/L)	Hardness (mg/L)	pH	Conductivity (μScm^{-1})	T (^0C)	TDS (mg/L)	Salinity (mg/L)	Turbidity (mg/L)	COD (mg/L)	*E. coli* (CFU/mL)	TOC (mg/L)	
IR_1996_S					8.1–8.5	112–187		100–260						[63]
IR_1996_S					8	116.3	15.7							
IR_2009-10_S	7.15–11.71		226.00–406.00	53.00–245	8.15–8.53	303.00–476.00	12.20–19.70	145.90–176.20	0.10–0.20	0.60–11.22		2.00–98.00	0.40–7.30	[65]
IR_2009-10_S	10.17		333.43	187.27	8.36	336.43	15.66	155.41	0.11	4.97		8.18	1.07	
IR_2009-10_W	10.00–11.46		108.00–524.00	51.56–206.92	7.56–8.72	0.23–130.00	14.88	0.24–156.00	0.00–0.30	0.87–7.22		0.00–77.00	0.25–7.15	
IR_2009-10_W	10.69		319.25	150.67	8.33	326.65	15.20–16.40	103.46	0.1	3.38		6.48	0.92	
IR_2009_10_S					7.58	243.78		121.51	0.12	1.17	31.45			[59]
IR_2011_S					7.4–8.0	232.0–316.0		150.1–223.1						[64]
IR_2011_S					7.7	260.1		184						
IR_2013_S	10.2–14.2	14.9–13.2	263.5-282.0	144–192										[97]
IR_2013_W	11.65	14.1	272.1	158										
IR_2019_S					8.50–7.70	153–132		179.27–161.34						[98]
IR_2019_S					8.35	138		169.62						
IR_2018_S					7.80–8.32	155–140		181.85–164.57						
IR_2018_S					8.13	147.67		173.89						
GM*					8			120						[61, 64]

*Global Mean of Some Major Rivers of the World. IR: Indus River: S and W along with the years indicates sampling period in summer and winter, respectively.

Table 4. Concentration of heavy metals and other parameters in the Indus River, in Leh Ladakh

Source ID	Value	Parameters																	Ref
		SiO_2 (mg/L)	U-238 (µg/L)	$^{234}U/^{238}U$	Rb (nmol/L)	Sr (nmol/L)	$^{87}Sr/^{86}Sr$	Ba (µg/L)	Fe (mg/L)	Mn (mg/L)	Zn (mg/L)	Si (mg/L)	Al (mg/L)	As (mg/L)	Cd (mg/L)	Pb (mg/L)	Cr (mg/L)	Ni (mg/L)	
IR_1991_S	Range		1.57–4.94	1.09–1.22	10–77	1396–3689	0.7104–0.7116												[39]
IR_1991_S	Mean		3.12	1.2	46.3	2175.5	0.7111												
IR_1996_S	Range	2.8–9.8																	[19]
IR_1996_S	Mean	6.2				113ppb	0.7104	15.7	27.8 ppb	<10 ppb	15.6								
IR_2009-10_S	Range								1.02–1.13	0.87–1.67									[65]
IR_2009-10_S	Mean								1.06	1.23									
IR_2009-10_W	Range								1.04–1.13	0.34–1.00									
IR_2009-10_W	Mean								1.07	0.62									
IR_2009_10_S	Range													0.001–0.099	0.012–0.036	0.043–0.275	0.019–0.275	0.001–0.062	[59]
IR_2009_10_S	Mean													0.075	0.024	0.111	0.024	0.016	
IR_2013_S	Range								0.3-1.4	0.146–0.177		27.2–92.57	0.002–1.88						[97]
IR_2013_W	Mean								0.6			62.47	0.842						
IR_2019_S	Range	2.12–1.65																	[100]
IR_2019_S	Mean	1.86																	
*GM		7.63																	

*Global Mean of Some Major Rivers of the World. IR: Indus River; S and W along with the years indicates sampling period in summer and winter, respectively.

mospheric CO_2 increases the concentration of carbonic acid in the water, accelerating chemical rock weathering along with H_2SO_4. Low pCO_2 values support the coupling of carbonate dissolution and sulphide oxidation, while C-ratio values between 0.75 and 0.9 indicate the protonation of meltwater due to the dissociation and dissolution of atmospheric CO_2. C-ratio values above 0.5 indicate that rapid calcite weathering is predominant over sulphide oxidation.

iii. Carbonate Hydrolysis: The low concentration or absence of CO_3^{2-} ions suggests hydrolysis of CO_3^{2-} to HCO_3^-. The dissolution of atmospheric CO2 further enhances the concentration of bicarbonate ions through CO_2 dissolution.

iv. Anionic Load: Studies indicate that the Indus River carries a higher anionic load compared to other Himalayan rivers. This is attributed to the dominance of carbonate minerals over silicate minerals, as shown by strong correlations between various ions such as Ca^{2+}- HCO_3^-, Mg^{2+}-HCO_3^-, Ca^{2+}-Mg^{2+}, Na^+- HCO_3^-, and Mg^{2+}-Na^+.

v. Nitrate (NO_3^-) Levels: NO_3^- concentrations in the Indus River range from <1 to ~3 ppm, which is relatively low compared to global averages and other neighbouring rivers. This suggests a minimal impact from anthropogenic and agricultural activities. However, reports indicate that nitrate levels can reach up to 25.6 ppm in streams near villages due to the use of fertilizers in agricultural activities. Therefore, caution should be exercised regarding drinking water from such areas.

vi. Microplastics: A research project found microplastic concentrations ranging from 60 to 340 MP/Kg DW (microplastic particles per kilogram of dry weight) in the Indus River. Despite having fewer people living along the Indus River in Ladakh compared to the Brahmaputra River in Assam, Arunachal, and Bangladesh, the microplastic levels were found to be comparable between the two rivers.

Overall, these findings provide insights into the chemical composition and environmental challenges faced by the Indus River, including the impact of weathering processes, carbonate hydrolysis, anionic load, nitrate pollution, and microplastic contamination.

Groundwater

According to a stable isotopic study conducted, the primary sources of groundwater recharge in Leh town are glacial and snow melts, contributing 44% and 39%, respectively [26, 45]. In contrast, rainfall has a lesser contribution of approximately 17% to groundwater recharge. Studies on various physicochemical parameters of groundwater in Leh town indicate that the dominant ionic species in the samples were Ca^{2+} and HCO_3^{2-}, suggesting carbonate weathering (Tables 5–7). Most of the samples belong to the Ca^{2+}-Mg^{2+}-HCO_3^- type, while the remaining samples follow the Ca^{2+}-Mg^{2+}-Cl^-- SO_4^{2-} composition [13, 20, 46].

Table 5. Concentration of major ions (mg/L) in the ground water, in Leh Ladakh

Source ID	Sampling period	Value	Parameters										Ref
			HCO_3	Ca	Mg	Na	K	F	Cl	NO_3	SO_4	PO_4	
HS1_1996_S	Summar-1996	Mean	94	27.4	1.1	300	22	6.7	90	0.3	225		[63]
HS2_1996_S	Summar-1996	Mean	939	13.8	1.6	610	80	17	425	0.6	115		
HS2_2011_W	Winter-2011	Mean	817.5	8.3	8.7	330.9	59.1	11.1	384.9	1.86	663.5		[47]
HS3_2011_W	Winter-2011	Mean	600.3	0.2	3.9	320.2	44.6	14.1	86.4	0.93	117.6		
HS4_2011_W	Winter-2011	Mean	275.8	7.2	7.3	101.3	9.1	5.7	6.5	1.05	40.9		
HS5_2011_W	Winter-2011	Mean	263.6	1.9	3.9	120.7	6.9	9.0	6.2	2.48	61.6		
HS6_2011_W	Winter-2011	Mean	207.4	1.1	4.1	80.2	5.04	11.8	9.0	0	46.7		
HS1_2011_W	Winter-2011	Mean	447.8	3.9	2.9	320.1	55.6	10.1	333.8	1.7	657.5		
GW_2013_S	Summar-2013	Range		11.77–45.11	2.92–26.35	0.1–31.9	0.8-3.2		2.13–4.97		9.39–13.70	0–0.47	[13]
GW_2013_S	Summar-2013	Mean		32.15	14.04	7.54	1.6		3.51		10.69	0.06	
GW_2013_W	Winter 2013	Range		47.03–107.40		4.87–45.41	1.01–97.71		12.53–27.42	0.0–0.2	11.53–83.41		[97]
GW_2013_W	Winter 2013	Mean		76.61			20.13		18.8	0.1	42.9		
GW_2015_S	Summar-2015	Range	9.48–54.50	25–123	14.26–68.43	100–420	10.05–36.88		10.81–39.24		0.21–0.71	0.01–0.17	[38]
GW_2015_S	Summar-2015	Mean	28.23	60.92	40.75	234.5	24.76		22.74		0.46	0.04	

HS: Hot springs; GW: Ground water; HS1: Chummathang; HS2: Puga hotspring; HS3: Changlung; HS4: Pulthang; HS5: Panamic; HS6: Gaik. S and W along with the years indicates sampling period in summer and winter, respectively.

Table 6. Physicochemical parameters of ground and lake water, Leh Ladakh

Source ID	Value	Parameters								Ref
		DO (mg/L)	Free CO_2 (mg/L)	Alkalinity (mg/L)	Hardness (mg/L)	pH	Conductivity (μS/cm)	T (⁰C)	TDS (mg/L)	
FW2_1996_S	Range					8.5–8.7	84–93	13.2–13.4		[39]
FW2_1996_S	Mean					8.6	88.5	13.9		
SL3_1932	Mean	7.4		255		9				[17]
SL3_2000	Mean	4.5		575		8	1058			
SL3	Range					8.9–9.02	3360–3740		2150–2393	[51]
SL4	Mean				3160	8.96	3550		2272	
SL5	Range				18292–21195	8.8–8.84	62720–64340		40141–41178	[96]
SL5	Mean				19743	8.82	63530		40659	
HS1_1996_S	Mean					7.5	1735			[63]
HS2_1996_S	Mean					8	3100			
HS2_2011_W	Mean					8	2790	84	1953	[100]
HS3_2011_W	Mean					7	2650	74	1855	
GW_2013_S	Range				90–188	7–8	205–849		134–565	[13]
GW_2013_S	Mean				135	7.55	441.51		291.22	
GW_2013_W	Range	5.9–9.6	11.6–19.2	160–310	140–300					[97]
GW_2013_W	Mean	7.9	16.1	257.4	220.1					
GW_2015_S	Range	9.27–10.65		202–696	81.25–837.11	7.13–8.58	139–1143	14.90–1960	66.40–563.0	[38]
GW_2015_S	Mean	10.03		494.49	235.99	7.7	488.74	17.24	238.5	

HS: Hot springs; GW: Ground water; HS1: Chummathang; HS2: Puga hotspring; HS3: Changlung; FW1: Chakratal Tso; FW2: Startspuk Tso; SL1: Pangong lake; SL2: Kiagar Tso; SL3: Tso morari; SL4: Tsokhar; SL5: Tsokhar Lake; S and W along with the years indicates sampling period in summer and winter, respectively.

Hot Springs

Ladakh is famous for its hot springs, which can be found in various locations such as Changlung, Pulthang, and Panamic in the Nubra Valley, Gaik and Chumathang in the Indus Valley, and Puga in the Puga Valley. These hot springs have temperatures ranging from 83 to 107°C, with Chumathang and Changlung being the hottest and Gaik being the coolest [47]. While temperatures exceeding 250 °C are expected at greater depths (3 km), studies using silica and cation geothermometry indicate that temperatures at shallower depths are around 150 and 250 °C [48].

To gain insights into the potential sources of recharge for the geothermal system's aquifer zone, stable isotopes of oxygen (^{18}O) and hydrogen (D) in the geothermal water can be analyzed. An isotopic analysis revealed that precipitation and groundwater are the primary sources of recharge for most hot springs [49]. However, in the cases of Puga and Chumathang, the isotopic composition suggests that their recharge may come from deeper sources, possibly associated with magmatic activity. This is supported by the elevated levels of trace elements, such as arsenic (As), which indicate mixing with high-temperature fluids from deeper regions.Reported studies on various physicochemical parameters of hot springs in Leh town are summarized in Tables 5–7. The major anions found in geothermal waters are HCO_3^-, Cl-, and SO_4^{2-}, while the major cations are Na^+ and K^+. In nonthermal waters, the composition is reversed. The concentrations of dissolved salts in thermal waters are mainly controlled by the processes of silicate weathering and ion-exchange kinetics. The presence of minerals like thenardite, pyrite, and jarosite in the basement rock encountered by high-temperature fluids leads to enrichment of Cl^- and SO_4^{2-} ions in the geothermal waters [47–49]. Considerable amounts of trace elements such as iron (Fe), boron (B), lithium (Li), strontium (Sr), manganese (Mn), aluminium (Al), molybdenum (Mo), zinc (Zn), and arsenic (As) have also been reported, indicating possible interaction between the geothermal waters and the surrounding rocks [47].

Two types of hot springs have been identified in Ladakh: periphery types, found in Changlung, Pulthang, Panamic, and Gaik, which demonstrate evidence of subsurface mixing of deep fluids with meteoric water; and volcanic types, found in Chumathang and Puga, characterized by their volcanic origin at the surface.The geothermal fields of Ladakh have the capacity to release approximately 2.9×10^7 moles/year of CO_2 into the atmosphere, with Changlung, Pulthang, and Panamic contributing 2.9×10^6 moles/year from the Nubra Valley, and Puga, Chumathang, and Gaik contributing 2.05×10^7 moles per year from the Indus and Puga valleys region [47]. According to the "Geothermal Atlas of India" published by the Geological Survey of India (GSI) in 1991, Panamik in the Nubra Valley and Chamuthang and Puga in the Indus Valley have the potential for geothermal power generation ranging from 3 to over 20 megawatts (MW) electricity. The concentrations of iron (Fe) and aluminium (Al) in the Ladakh region's geothermal waters vary from 5 to 118 µg/L, while boron (B) is a major ion in the geothermal waters of Puga and Chumathang, with concentrations ranging from 444 to 30194 µE [18].

Table 7. Heavy metal concentrations in ground and lake water, Leh Ladakh

Source ID	Value	Parameters											Ref
		SiO_2 (mg/L)	Rb (nmol/L)	Sr (nmol/L)	$^{87}Sr/^{86}Sr$	Ba (µg/L)	Fe (mg/L)	Mn (mg/L)	Zn (mg/L)	Si (mg/L)	Al (mg/L)	As (mg/L)	
FW1_1991_S	Mean		38	1298	0.7093								[39]
FW2_1991_S	Mean		13	1340	0.7238								
FW2_1996_S	Range	0.3–1											[63]
FW2_1996_S	Mean	0.6		60		9	ND	ND	<10				
SL1_1991_S	Mean		521	1192	0.7102								[39]
SL2_1991_S	Mean		926	81	0.7302								
SL3_1991_S	Mean		46	605	0.7168								
SL4_1991_S	Mean		4056	625	0.7198								
SL3_2000	Mean			0.002 ppm									[17]
HS1_1996_S	Mean	114		336		36 ppm		<10	<10				[63]
HS2_1996_S	Mean	190		294			80	92	2		33	181	
HS2_2011_W	Mean	3660											[100]
HS3_2011_W	Mean	3733											
GW_2013_W	Range						0.07–3.463	0.146–0.919		11.69–279.0	0.016–2.838		[97]
GW_2013_W	Mean						0.95	0.19		63.2	1.62		
GW_2015_S	Range						1.01–5.01	0.01–0.99	0.07–3.67				[38]
GW_2015_S	Mean						1.95	0.61	0.89				

HS: Hot springs; GW: Ground water; HS1: Chummathang; HS2: Puga hotspring; HS3: Changlung; FW1: Chakratal Tso; FW2: Startspuk Tso; SL1: Pangong lake; SL2: Kiagar Tso; SL3: Tso Morari; SL4: Tsokhar; SL5: Tsokhar Lake; S and W along with the years indicates sampling period in summer and winter, respectively.

Lake Water

The literature review conducted on lakes in Ladakh highlights the presence of two types of lakes, namely fresh and saline (brackish) lakes. The composition of these lakes varies significantly based on the geographical characteristics of the area and the level of evaporation they have undergone. The lakes like Tsomoriri and Tsokar exhibit high salinity resulting in exceptionally high salinity and conductivity due to the absence of drainage rivers leading to the ocean, which allows salts and minerals to accumulate from the surrounding mountains. This phenomenon is primarily attributed to the prevailing cold desert climate, and high evaporation rates, characterized by low annual rainfall of approximately 100 mm [19, 50–52]. The suitability of these lakes for various purposes, as well as their physical and chemical parameters, are summarizedin Tables 6–9.

ASSESSMENT OF HYDROCHEMICAL PARAMETERS OF THE LADAKH REGION

pH

pH is a crucial parameter for assessing water quality as it reveals important information about the chemical equilibrium and solubility of various substances in water. The pH value of water is typically 7, indicating neutrality. Any deviation above or below 7 suggests natural or human-induced changes in the water chemistry [53, 54]. The previous studies reveal that pH ranges of all water resources fall between 7.1 and 9.0, indicating that they are slightly alkaline in nature. However, apart from saline lakes, all these water sources are within the acceptable limits recommended by World Health Organization (WHO) and BIS, which is between 7 and 8.5 (Tables 1, 3, and 6).

Electrical Conductivity

Conductivity is an important parameter that indicates the concentration of dissolved ions, or the amount of soluble salts, in a body of water. Significant changes in conductivity can suggest the presence of discharge or contamination in the aquatic environment [54]. As evident from the data presented in Tables 1, 3, and 6, the conductivity levels ranged from 88.5 to 63530 (µS/cm), with higher values in saline lakes resulting from the dissolution of ionic species from the surrounding rocks. The WHO sets a standard that the electrical conductivity value should not exceed 400 µS/cm [55]. Previous reports indicate that all water sources, except for hot springs and saline lakes, are within the permissible limit [53]. A study conducted in 2000, measured the electrical conductivity of Tsomorari lake as 1058 µS/cm [17]. However, subsequent studies have shown values exceeding the permissible limit, indicating an increase in the dissolution of ionic compounds and evaporation. The classification of water quality based on electrical conductivity is shown in Appendix 1 [53].

Total Dissolved Solids (TDS)

Water has a natural ability to dissolve various minerals and salts, both organic and inorganic. This includes while

Table 8. Concentration of major ions (mg/L) in the lake water, Leh Ladakh

Source ID	Sampling period	Value	Parameters										Ref
			HCO_3	Ca	Mg	Na	K	F	Cl	NO_3	SO_4	PO_4	
FW1_1991_S	Summar-1991	Mean		26.2	7	12.6	3.9		12.1		36		[39]
FW2_1991_S	Summar-1991	Mean		18.3	10.1	20.5	4.7		17.6		20.3		
FW2_1996_S	Summar-1996	Range	53.6–60.3	16.6–20.1	2.8–3.3	1.4–3.3	1.7–2.1	0.2	0.8–2.6	0.2–1.2	2.8–3.5		[63]
FW2_1996_S	Summar-1996	Mean	56.95	18.2	3.1	2	1.9	0.2	3.2	0.6	3.2		
SL1_1991_S	Summar-1991	Mean		3440	0.4	2.9	0.2		0.3		0.3		[39]
SL2_1991_S	Summar-1991	Mean		1400	0.2	1.4	0.3		0.3		2.4		
SL3_1991_S	Summar-1991	Mean		12000	0.2	1.4	17940		21655		0.4		
SL4_1991_S	Summar-1991	Mean		99200	19.6	46	14.2		60.9		80.1	0.02	
SL3_1932	1932	Mean	599	13	182	89	56		22		517		[17]
SL3_2000	2000	Mean	325	25.4	332.4	102.9	3.45	0.849	34.4	0.427	493.1		
SL3	NA	Range	0–2	30–40	744–750	89–1493	98–319	0.44–0.50	24		32–144	0.03–0.04	[51]
SL4	NA	mean	1	35	747	791	209	0.47	24		88	0.04	
SL5	NA	Range	2–6	760–1840	3330–4690	628–1493	1470–1960	0.42–0.60	8850–9206		16–36	0.16–0.43	[96]
SL5	NA	Mean	4	1300	4010	1061	1715	0.51	9028		26	0.3	

FW1: Chakratal Tso; FW2: Startspuk Tso; SL1: Pangong Lake; SL2: Kiagar Tso; SL3: Tso Morari; SL4: Tsokhar; SL5: Tsokhar Lake; NA: Data not available; S and W along with the years indicates sampling period in summer and winter, respectively.

Table 9. Suitability of different water sources based on residual sodium carbonate (RSC), magnesium hazard (MH), percent sodium (%Na), sodium adsorption ratio (SAR) and corrosivity ratio (CR) [101]

Source ID	TH	RSC	MH	%Na	SAR	CR	Remarks
IR_1991_S	76.8	0.8	18.3	29.3	0.7	0.6	Most of the water from Indus River, Glacial Melts and Groundwater are soft, <0 RSC level, Low MH, <60 %Na level, falls under C1S1 & C1S2 categories (SAR) and low CR make the water quality good to excellent for agriculture and can be transported through iron pipes.
IR_1996_S	78.9	0.6	15.8	23.8	0.5	0.5	
IR_2009-10_S	351.8	-3.1	26.1	43.4	2.0	2.8	
IR_2009-10_W	299.7	-2.6	32.0	48.8	2.2	2.7	
IR_2011_S	94.3	0.8	18.5	22.3	0.5	0.5	
IR_2013_W	128.4	-1.3	12.2	70.4	2.7	NA	
IR_2019_S	99.3	0.5	20.2	31.2	0.8	0.7	
IR_2018_S	74.3	1.1	18.8	22.0	0.4	0.5	
FW1_1991_S	94.9	-0.9	21.1	33.2	0.8	NA	
FW2_1991_S	88.2	-0.9	35.6	47.0	1.3	NA	
FW2_1996_S	58.5	0.4	14.6	15.5	0.2	0.3	
GW_2013_S	139.3	-1.4	30.4	16.5	0.4	NA	
GW_2013_W	191.5	-1.9	0.0	20.8	0.0	NA	
GW_2015_S	323.5	-2.8	40.1	71.8	8.0	2.3	
UG_GM_2010_EMP	746.7	-3.2	15.6	11.0	0.5	0.5	
UG_GM_2010_PMP	547.7	-2.6	19.1	12.5	0.5	0.2	
UG_GM_2010_LMP	1313.0	-5.6	17.5	8.6	0.5	0.0	
LT_GM_2019_S	37.0	0.1	12.7	8.7	0.1	0.4	
SK_GM_2019_S	66.8	0.2	5.7	8.3	0.1	0.4	
CN_GM_2019_S	102.2	0.2	15.7	9.0	0.2	0.8	
LT_GM_2018_S	29.8	0.2	12.6	24.4	0.2	0.5	
SK_GM_2018_S	13.7	1.0	49.9	76.7	0.4	0.2	
CN_GM_2018_S	64.2	0.8	13.6	13.3	0.1	0.4	
SL1_1991_S	8601.7	-86.0	0.0	0.1	0.0	NA	Saline water lakes are hard to very hard range, <0 RSC level, high MH, >40 %Na level, falls under C3S1 categories (SAR) and high CR value make the water quality unsuitable for agriculture as well as transportation through iron pipes.
SL2_1991_S	3500.8	-35.0	0.0	0.1	0.0	NA	
SL3_1991_S	30000.8	-300.0	0.0	59.9	0.0	NA	
SL4_1991_S	248082.3	-480.8	0.0	0.1	0.1	NA	
SL3_1932	796.9	2.1	93.3	42.6	1.9	1.9	
SL3_2000	1459.6	-9.1	92.9	22.9	1.7	3.5	
SL4	3224.9	-32.0	95.5	56.1	8.6	251.9	
SL5	20092.0	-199.5	75.5	34.3	4.6	6462.1	
HS1_1996_S	73.1	0.8	3.9	91.9	21.6	7.7	The parameters TH, RSC, MH, % Na, SAR and CR levels for the hot springs are above the desired level for agricultural purposes. Hence, highly unsuitable for agriculture and transportation through iron pipes.
HS2_1996_S	41.2	15.2	10.4	97.8	58.5	1.5	
HS2_2011_W	57.2	13.1	51.4	95.8	27.0	3.0	
HS3_2011_W	17.0	9.8	94.2	98.9	47.9	0.8	
HS4_2011_W	48.7	4.1	50.4	88.4	9.0	0.4	
HS5_2011_W	21.0	4.2	67.6	95.7	16.2	0.6	
HS6_2011_W	20.1	3.3	79.7	94.2	11.0	0.6	
HS1_2011_W	21.7	7.2	42.5	98.2	42.4	5.2	

the major cations are Na^+, K^+, Ca^{2+}, Mg^{2+}, HCO_3^-, Cl^-, and SO_4^{2-} ions and many others. When these minerals and salts dissolve in water, they can impart an unpleasant taste and colour to it. The concentration of dissolved ions in water is reflected by the measurement of total dissolved solids (TDS). Higher TDS values indicate a greater concentration of dissolved ions in water. When using water, TDS is an important parameter to consider. For drinking purposes, it is desirable for water to have a TDS limit of 500 mg/L, with a maximum allowable limit of 2000 mg/L. The TDS values for different water sources mentioned in Tables 1, 3 and 6 fall within the desirable TDS limit, except for the waters found in saline lakes and hot springs.The classification of water quality based on TDS is described in Appendix 2 [53].

Total Hardness

Chemical weathering of rocks has a significant impact on the chemical composition of water sources in Ladakh, particularly in relation to the presence of Ca^{2+}, Mg^{2+}, CO_3^{2-}, HCO_3^-, Cl^-, and SO_4^{2-} ions, which are responsible for determining the total hardness (TH) of the water. While calcium carbonate is used as a representation of total hardness, other chemical components also contribute to this measurement. The levels of ions that contribute towards hardness of water indicate that the primary source is the chemical weathering of rocks. According to the standards set by the Bureau of Indian Standards (BIS), the acceptable and permissible limits for total hardness in drinking water are 200 ppm and 600 ppm, respectively. Based on this criterion, all the water sources fell within the permissible limit, except for the water from saline and hot springs [53].The classification of water quality based on total hardness is shown in Appendix 3.

Heavy Metals

Heavy metals pose a significant threat to humans and other organisms as they are highly carcinogenic and can cause various diseases. A study conducted on groundwater in Leh city found significant pollution due to the accumulation of Cr, Cd, Ni, Mn, Fe and Cu (Table 7) [56]. The contamination was worsened using pesticides, agricultural chemicals, and soak pit effluents. A study in the Upper Indus River Basin of Ladakh by Lone et al. [57] found that arsenic levels in groundwater varied from 1.1 to 86 µg/L, with an average of 22 µg/L. Approximately 70% of analysed water samples had arsenic concentrations above 10 µg/L above the WHO limit for drinking water. Arsenic levels increased with rising water temperature and well depth, indicating a positive correlation between arsenic and temperature, suggesting that higher temperatures facilitate arsenic release [24]. The increase in tourism and urbanization in the region has led to a surge in groundwater extraction. As groundwater extraction intensifies, water levels decrease, prompting people to extract water from deeper depths, thereby increasing the risk of arsenic contamination in groundwater. Arsenic (As) concentrations were found to be higher in hot springs than in local groundwater, with volcanic and ophiolitic melange aquifers being identified as primary sources of the metal. It was recommended to paint the wells red as arsenic is poisonous and carcinogenic, posing a risk to millions of people. High-temperature thermal water exhibited better reactivity and higher metal concentrations, possibly due to leaching from the host rock [58]. Fe and Al concentrations varied from 5 to 118 µg/L in the Ladakh region, while boron concentrations in geothermal waters of Puga and Chumathang ranged from 444 to 30194 µE. Arsenic (As) concentrations were also high in geothermal springs, indicating a magmatic source for these fluids [47]. Heavy metal concentrations in Ladakh, except in hot springs and saline water lakes, were within permissible limits. However, a sensitivity analysis conducted on groundwater revealed that factors such as body weight, exposure length, and metal content were the main determinants of overall health risks. Another study found concentrations of heavy metals such as Cd, As, and Pb above the WHO's permissible limit in the Indus River, irrigation water, and stagnant water at various locations in Leh [59].

Other Chemical Species

The higher levels of Cl^- and SO_4^{2-} ions in the Indus River can be attributed to factors such as the dissolution of evaporates, the burning of sulfur-containing fossil fuels, and the contribution from biological sources through atmospheric transport [40, 60]. However, it has been reported (Table 2) that the concentration of NO_3^- ions in the Indus River is relatively low compared to the global average (1 mg/L) and other nearby rivers. The values fall below the permissible limit set by the Environmental Protection Agency (EPA) of 10 mg/L. This indicates a minimal impact from human activities and agriculture, and thus there is no significant concern for human health [40, 61].

According to a report, higher levels of Mg, Na, K, Mn, Ca, Cl, S and Al were found in the Indus River water collected near the city area of Leh [62]. This suggests an impact of human activities on the water sources in that area. Additionally, the concentrations of Al and alkalinity exceeded the limits prescribed by the WHO. However, few other studies have indicated that the water chemistry in the Indus River is primarily influenced by the surrounding geology (lithology) and not by human activities [39, 63, 64]. They found no evidence of anthropogenic influences on the water chemistry and concluded that most surface water in the region is suitable for drinking, except for salt lakes and hot springs. These studies did note that the TDS concentration was moderate compared to other major rivers in the Himalayan region, such as the Ganges and Brahmaputra. Another study reported that anthropogenic activities and agricultural waste are the main factors affecting the water quality of the Indus River [65].They found that these effects are more prominent during the summer season, indicating the impact of tourism on water quality.

HYDROCHEMICAL FACIES IN DIFFERENT SOURCES

Piper Diagram

The Piper trilinear diagram, developed by Piper in 1944, is a graphical representation used to analyse and compare the chemical composition of water samples. It displays the relative concentrations of different ions present in the water, allowing for the identification of specific chemical facies or patterns [66]. In the case of Ladakh's water sources, the diagram is used to examine the hydrochemical facies of the various water samples. These facies reflect the consequences of chemical interactions between the water and the minerals found in the lithologic framework (the geological materials forming the region).

Based on the data shown in Tables 1, 2, 5 and 8, the diagram provides a comparative review of the hydrochemical facies of different water sources in Ladakh (Fig. 3). The diagram reveals the dominant ions and their relative concentrations

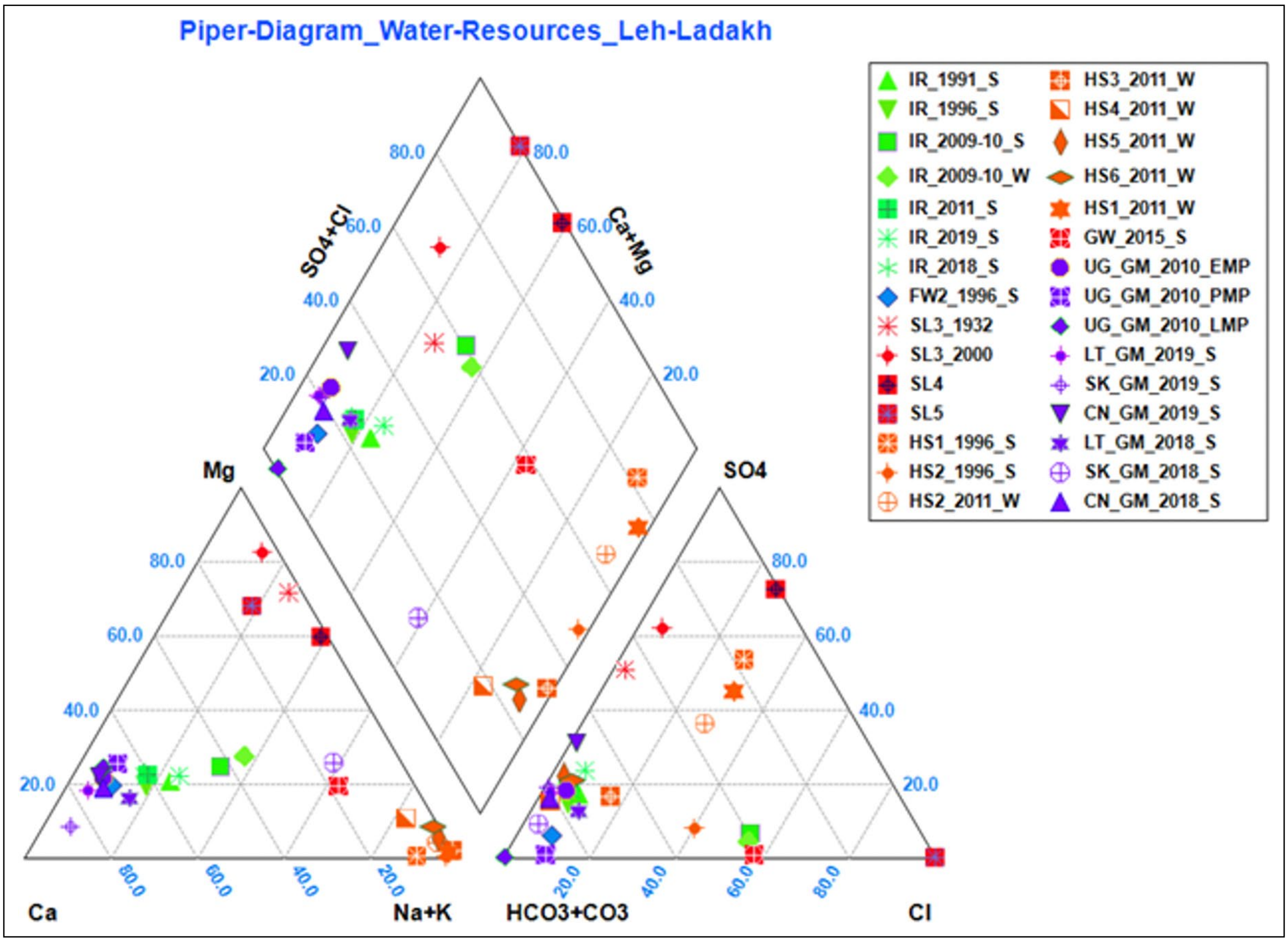


Figure 3. Piper diagram indicating ionic concentration of water samples collected from different regions of Ladakh. Data obtained and summarized from Ref. [13, 17, 30, 39, 40, 47, 51, 63–65, 96, 97].

in each water sample, indicating the type of weathering and the corresponding chemical facies. According to the diagram, freshwater lakes, and river water in Ladakh fall into the Ca^{2+}-Mg^{2+}-HCO_3^- type of facies, which indicates carbonate-type weathering. This suggests that the chemical composition of these water sources is influenced by the dissolution of carbonates present in the geological materials.

Hot water springs in Ladakh exhibit Na^+-K^+-Cl^--SO_4^{2-} and Na^+-K^+-HCO_3^- types of chemical facies. This suggests that the chemical composition of the water in these springs is primarily controlled by silicate weathering processes, where the dissolution of silicate minerals contributes to the presence of sodium, potassium, chloride, sulfate, and bicarbonate ions. Saline lakes in Ladakh display Ca^{2+}-Mg^{2+}-Cl^- and Ca^{2+}-Mg^{2+}-HCO_3^- types of facies. These facies indicate the prevalence of chloride and bicarbonate ions, along with calcium and magnesium ions, in the water samples. The presence of these ions indicates the influence of evaporative processes and the accumulation of salts in these saline lakes.

Durov Diagram

The trilinear Durov diagram, is a plot that is commonly used in hydrogeochemistry to analyse and compare the chemical composition of water samples, particularly in groundwater studies. This trilinear plot consists of two distinct triangular plots representing major cation and anion concentrations in water samples (Fig. 4). The concentrations of these ions are expressed in milliequivalents. The two triangular plots intersect at a common base, forming a rectangle. The purpose of the trilinear Durov plot is to visualize and analyse the chemical facies or composition of different water sources. By plotting the data points representing the chemical composition of water samples onto the rectangular grid at the base of each triangle, it becomes easier to identify patterns and variations in the composition. This plot provides a comprehensive representation of the water chemistry and allows for the comparison of different water sources based on their chemical characteristics. In addition to the main ion concentrations, two optional water quality metrics can be included in the plot. These metrics could be parameters such as pH, TDS, or electrical conductivity. By incorporating these metrics, the Durov plot allows for a direct comparison of multiple groundwater properties [67]. The Durov diagram, originally designed for groundwater water quality assessment, has been extended to evaluate quality of different water resources in Ladakh. The analysis includes groundwater, Indus River water, freshwater lakes, water from glacial melts, hot springs, and saline lakes.The dia-

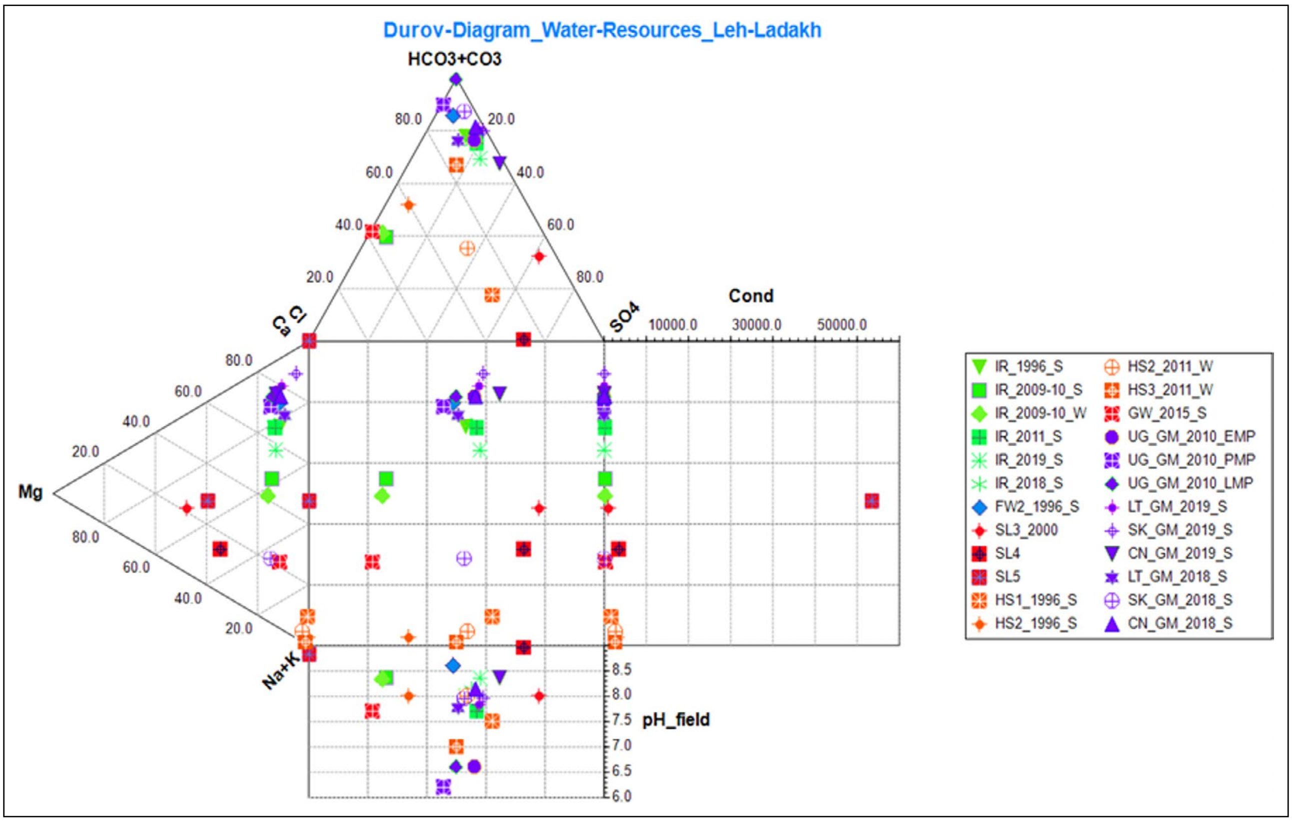


Figure 4. Durov diagram indicating water evolution pattern of water samples collected from different water resources of Ladakh. Data obtained and summarized from Ref. [13, 17, 30, 39, 40, 47, 51, 63–65, 96, 97].

gram reveals that groundwater, Indus River water, freshwater lakes, and water from glacial melts are characterized by the dominance of Ca^{+2} and HCO$_3^-$ ions, indicating the prevalence of carbonate rock weathering. On the other hand, hot springs exhibit dominance in Na$^+$-K$^+$-Cl$^-$-SO$_4^{2-}$ and Na$^+$-K$^+$-HCO$_3^-$ types of chemical facies. This observation suggests a different chemical composition associated with hot springs, potentially influenced by geothermal processes. Additionally, the prevalence of Ca^{2+}-Mg^{2+}-Cl$^-$ and Ca^{2+}-Mg^{2+}-HCO$_3^-$ types of facies in saline lakes aligns with the results obtained from the diagram. This confirms the chemical facies composition in saline lakes, where the dominant ions are calcium, magnesium, chloride, and bicarbonate. Furthermore, it can be deduced that water from groundwater, the Indus River, freshwater lakes, and glacial melts exhibits good quality with no contamination. However, water from hot springs and saline lakes indicates moderate to low quality, with high concentrations of sodium, chloride, and sulphate ions.

SUITABILITY OF WATER FOR AGRICULTURE

Only 20% of farmers in Ladakh have access to river water for irrigation, while the remaining 80% rely solely on glacier as their water source [12]. One of the primary uses of freshwater is for agricultural purposes, accounting for approximately 70% of annual global freshwater extraction [68]. The suitability of water for irrigation depends on the types and concentrations of dissolved salts present. The evaluation of irrigation water focuses on identifying unwanted elements, and its potential as a source of plant nutrients is considered only in specific circumstances. The United States Department of Agriculture (USDA) classification and various parameters such as Sodium Adsorption Ratio (SAR), Percent sodium (%Na), Residual Sodium Carbonate (RSC) and Corrosivity Ratio (CR) are utilized to determine the suitability of water for agricultural.Similarly,magnesium hazard (MH) is also one of critical parameter for estimating suitability of water for irrigation [69].

Sodium Adsorption Ratio (SAR)

Increased sodium content in water has a negative effect on soil characteristics and reduces soil permeability. When irrigation water has higher concentrations of Na$^+$ ion, it decreases soil absorptivity and leads to a deficiency of calcium, causing deflocculation and weakening of soil structure. To assess the suitability of water for irrigation and evaluate potential sodium-related risks, the sodium adsorption ratio (SAR) is used [70]. Figure 5 presents a salinity diagram (prepared by using Aquachem 10), plotting SAR against electrical conductivity (EC), which allows for the classification of irrigation water into different classes to determine its impact on soil salinity. The majority of Indus River samples and glacial melt water samples were classified as C1S1, indicating low salinity and sodium hazard, making them excellent for irrigation across various soil types (Table 9). Some Indus water and groundwater samples fell into the C2S1 class, indicating medium salinity hazard and low

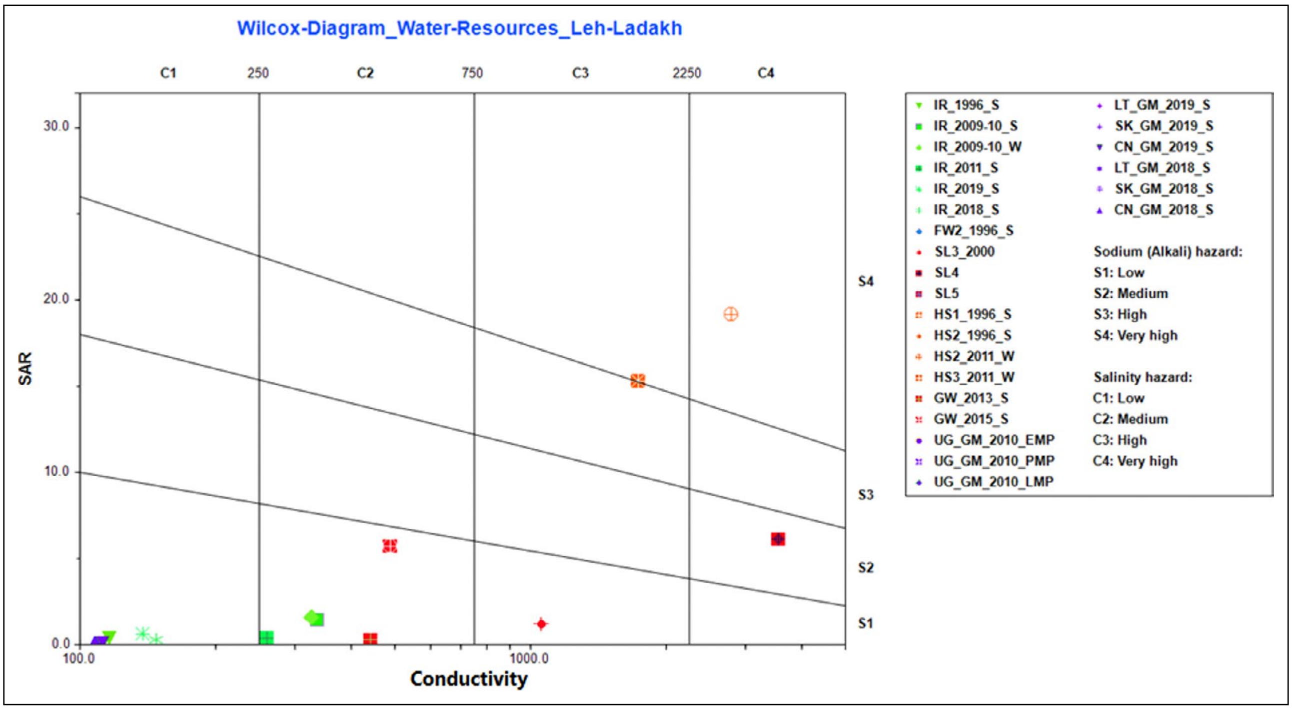


Figure 5. Wilcox diagram indicating sodium and salinity hazards of water samples collected from different water resources of Ladakh. Data obtained and summarized from Ref. [13, 17, 30, 39, 40, 47, 51, 63–65, 96, 97].

sodium (alkali) hazard, making them ideal for agricultural purposes. The water sample from the saline lake was categorized as C3S1, representing low alkali hazard but high salinity hazard, making it unsuitable for agricultural use. The hot spring water fell into the C3-C4S4 class, indicating very high alkali and salinity levels, making it unsuitable for agricultural purposes.

Residual Sodium Carbonate (RSC)

When there is an excess of carbonate compared to the levels of calcium (Ca) and magnesium (Mg), the extra carbonate combines with Ca and Mg and precipitates as solid material. As a result, the levels of Ca and Mg decrease, leading to an increase in SAR levels and the percentage of sodium. This, in turn, negatively affects the water quality for agricultural purposes. According to the value of RSC, the water quality is classified as <0 (very good), 0–2.5 (good), 2.5–5.0 (marginal), 5.0–7.5 (poor) and >7.5 (harmful) [71]. All the water sources except for hot springs were considered good to very good for agricultural use.

Percentage Sodium (%Na)

The percentage of sodium (%Na) is a significant factor to consider when examining the risks associated with sodium. The presence of sodium in soil leads to a decrease in soil permeability.The classification of water quality on the basis of sodium percent is given in Appendix 4 [72].

Magnesium Hazard (MH)

MH is a measurement that signifies the extent of harm caused to the soil structure due to the presence of magnesium in irrigation water. When the groundwater contains a high concentration of Mg^{2+}, it results in soil alkalinity. Additionally, a significant quantity of water gets adsorbed between magnesium and clay particles, thereby reducing the soil's ability to absorb water, which negatively affects crop growth. If MH exceeds 50, it indicates that the groundwater is detrimental and not suitable for irrigation. Conversely, if MH is less than 50, it suggests that the groundwater is appropriate for irrigation [72]. Based on MH all the river water, glacial melts, ground water and freshwater lake samples fall under suitable category for agricultural use while water hot springs and saline lake water fall under not suitable for agriculture (Table 9).

Corrosivity Ratio (CR)

The corrosivity ratio (CR) plays a crucial role in deciding whether water can be transported through metal pipes [38, 65]. When the CR value is below one, any type of metal pipe can be utilized for water delivery. Conversely, if the CR value exceeds one, water cannot be conveyed through metal pipes due to the higher risk of corrosion. Except for water sourced from saline lakes and hot water springs, the majority of water sources are generally appropriate for transportation through metal pipes in this region (Table 9).

IMPACT OF URBANIZATION

The National Geological Monument status has been conferred upon the varied geological features of the Himalayan region in Ladakh by the Geological Survey of India. Situated at an elevation of over 3000 meters in northwest India, Ladakh, also known as the "region of high passes," has become a sought-after tourist spot worldwide [23]. In recent

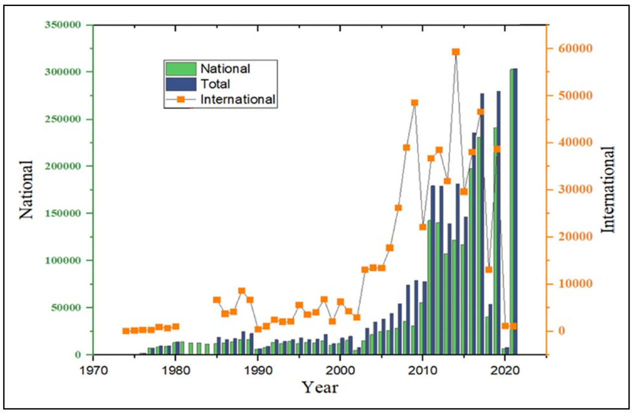


Figure 6. Tourists (national and international) arrival in Ladakh over last five decades. Data obtained from ref [75, 76].

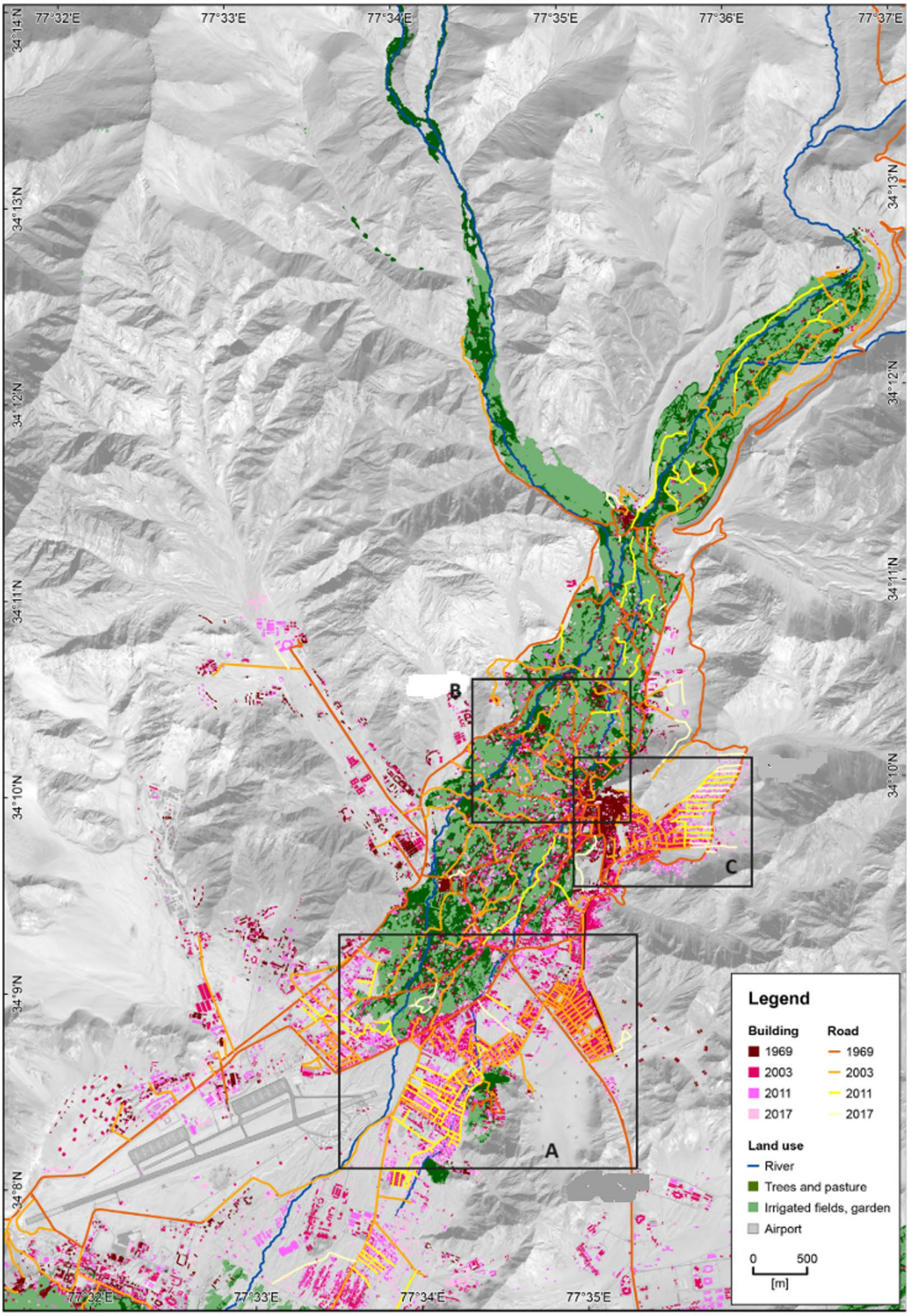
years, there has been a significant increase in urbanization and tourism in Ladakh, an environmentally vulnerable area. This rapid growth poses a serious threat to the region's environment, particularly in terms of water availability, which is further exacerbated by the impact of climate change [12, 14]. Despite its remote location, Ladakh is not immune to urbanization pressures, and both districts, Leh and Kargil, have experienced a steady rise in urbanization rates according to India's census reports from 1980, 2001, and 2011, with a decline of the rural population [7, 73]. The urbanization rates being 12.7, 23.4, and 34.2 in Leh and 5.3, 8.6, and 11.6 in Kargil, respectively, for these years. The Leh district has become one of the fastest urbanizing places in Ladakh due to its role as the administrative hub and the influx of floating populations such as army personnel and tourists [74]. The tourism industry plays a crucial role in Ladakh's local economy and has witnessed substantial growth since it opened its doors to foreign tourists in 1974. The number of visitors to Leh has multiplied over the years, with a significant increase observed between 2010 and 2022 (Fig. 6) [14, 75, 76]. This surge can be attributed to improved air connectivity and the expansion of domestic tourism driven by India's growing middle class. Despite the recent population increase, Ladakh's overall population remains relatively small (app. 2,75,000), with the majority residing in Leh and Kargil. However, due to security concerns related to neighbouring countries like China and Pakistan, an estimated 100,000 military personnel are stationed in Leh [12].

A study conducted in Lanzhou, a semi-arid region in China along the Yellow River, highlighted the degradation of groundwater quality due to arid climate conditions and excessive groundwater extraction [77]. Similar concerns arise in Ladakh, where rapid urbanization, driven by the booming tourism sector, may further deteriorate groundwater quality as it is heavily exploited to meet increasing demands. Some reports have revealed bacterial contamination in the spring-fed water pipeline system supplying the Chubi region of Leh. Although spring water has traditionally been considered safe for drinking in Ladakh, this contamination raises concerns about its reliability as a water source [74].

Asmoay et al. [78] studied the dry region of Nile Valley examined the impact of both natural factors and human activities on water contamination.The study found that 21% of the water samples analysed using the Water Quality Index were unsuitable for human consumption. Carcinogenic metals like lead (Pb) and cadmium (Cd), as well as total hardness, Na^{+}, K^{+}, Cl^{-}, and SO_4^{2-}, exceeded the acceptable ranges set by the WHO. In one of the towns of Leh district, there has been a significant departure from the traditional dry sanitation practice. The town has introduced water-intensive flush toilets and is disposing of untreated grey and black water in soak pits or septic tanks. However, the installation of a sewerage system is only partially functional and will take years to become fully operational [20, 74].This situation poses a huge threat of shallow groundwater pollution in the town. It is well known that even a minor change in the pH of water can accelerate the weathering of rocks, leading to changes in the chemical composition of water by increasing the dissolution of cations and anions [79]. This, in turn, results in elevated levels of TDS, turbidity, electrical conductivity (EC), and other parameters. Due to the heavy strain of tourism, the impact of these factors on the groundwater of this town is already evident. In the study, 75% of the samples showed higher levels of turbidity, and 10% exceeded the desired range for EC and TDS [74].

The tourism sector is predicted to experience significant growth as Odisha's Mayurbhanj district and the Union Territory of Ladakh have been recognized in TIME Magazine's '50 extraordinary destinations to explore' in their list of the 'World's Greatest Places of 2023' [80]. This acknowledgment highlights the appeal and uniqueness of these two Indian locations as tourist destinations. Some recent studies have examined the effects of rapid urbanization on water quality, particularly in semiarid regions and the results of which are summarized in Table 10 [3, 4, 8, 81–86].

UN-Habitat lists durable structures, population density, availability of clean water, access to better sanitation, and utility connectivity as some important markers of urbanization [87]. As mentioned previously availability of water in Leh is under heavy stress due to unplanned extraction of water resources especially groundwater by the ongoing climate change and anthropogenic processes of population expansion, urbanization, tourist influx, etc. Over the past few years, there has been a rapid expansion of housing settlements, encompassing both agricultural and barren lands, alongside a significant densification of urban areas. In one such report, 9400 new buildings were built between 2003 and 2017 alone, which is equal to the entire number built from 1969 to 2003 [88]. The overall built-up area grew almost five times during this time, from 36 hectares in 1969 to 196 hectares in 2017. As a result, from 1% in 1969 to 8% in 2017, the amount of agricultural land lost to building operations increased. A multi-temporal analysis of satellite imagery spanning from 1969 to 2017 illustrates the evolution of urban sprawl in Leh over the past fifty years as shown in Figure 7 and 8 [88]. A growing tourism industry, embrace of urban lifestyles, development of ad-



Satellite Images: Corona 30 Jul 1969, Quickbird 7 Nov 2003, 17 Jul 2006, Worldview 27 Nov 2011, Pléiades 22 Aug 2017
DEM: ASTER GDEM; Draft and Cartography: S. Schmidt, J. Dame, N. Harm

Figure 7. Urban development of Leh between 1969 and 2017. A: Housing Colony, Skalzangling and Ibex Colony constructed for residential purposes, B: Conversion of agricultural lands into built-up areas in Sankar and Chanspa, C: Residential and administrative quarter Skampari. Reproduced under Creative Commons License from an Open Access Article Ref. 88 (Elsevier).

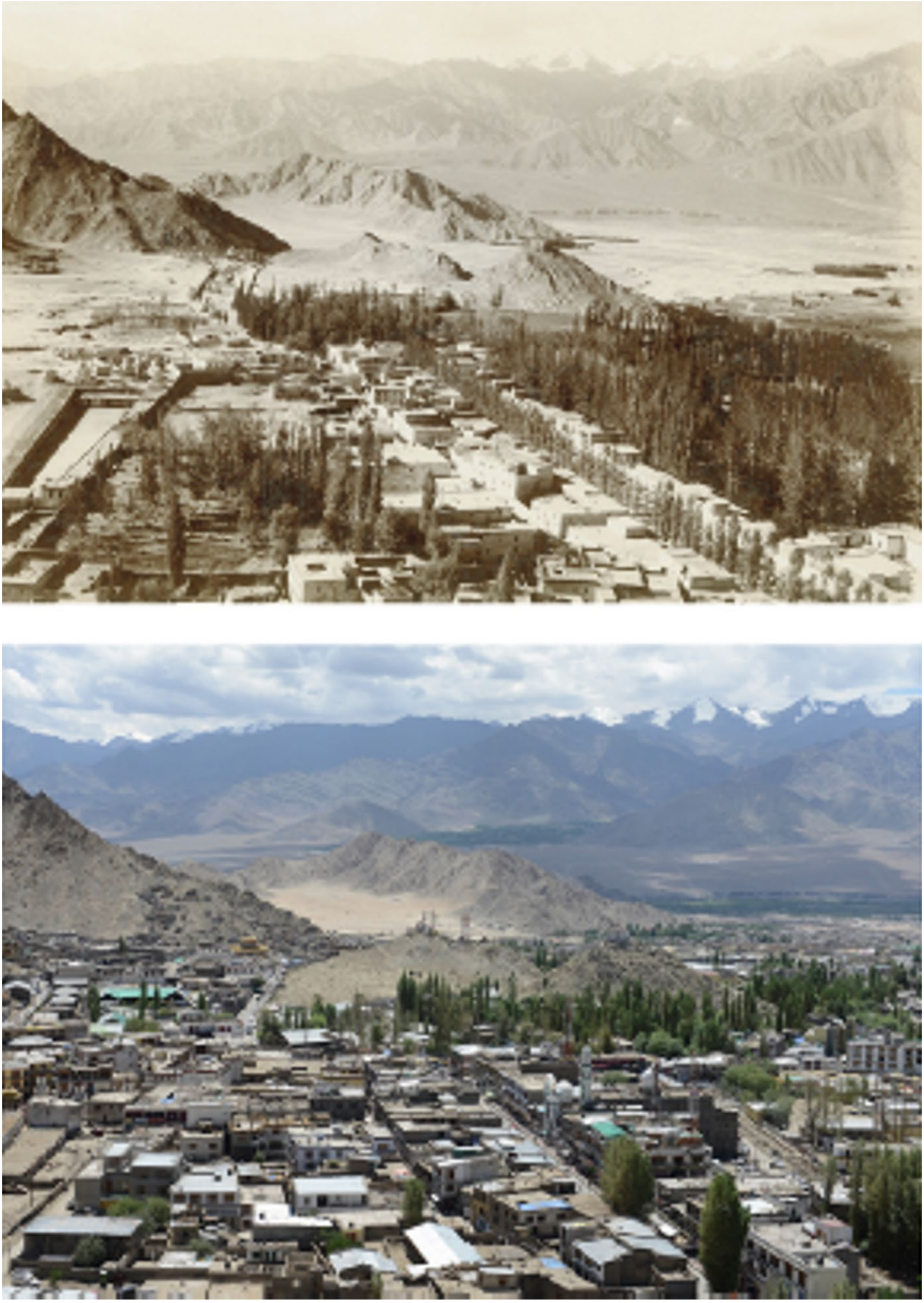


Figure 8. Repeat photography of Leh, taken from Tsemo Hill. The photographs show the axis of the main bazaar as a key urban structure. At the time of the early twentieth century, the large number of shops reflects the importance of trading activities for the small town. Recent urbanisation is characterised by intensive building activities in the centre and periphery of Leh, which reflects the growing diversity of services and functions for the region (upper photograph (a): C.G. Rawling 1903–1905; lower photograph (b): M. Nüsser 2013. Reproduced under Creative Commons License from an Open Access Article Ref. 88 (Elsevier).

Table 10. Recent studies on the impact of rapid urbanization on water quality with special reference to the semiarid areas

Sr. no.	Study region	Outcome	Ref
1.	Semi-arid region, Greece	A brief period of drought has the potential to trigger water crises in the region, creating a scarcity of water during the summer months. This may result in competition for water resources between tourists, rural activities, and even small-scale agricultural operations in the present and future.	[81]
2.	Liangjiang New Area, China	Urbanisation had detrimental consequences on macroinvertebrate community compositions in terms of taxonomic richness, diversity, and Ephemeroptera, Plecoptera and Trichoptera (EPT) species richness.	[82]
3.	Semi-arid Region of Northwest China	The study found that around 5.88% of the water samples were unsuitable for human consumption. The risk associated with water contamination was found to be significantly higher for children, indicating that they are more vulnerable to the effects of water pollution. Nitrogen and fluoride were identified as the most hazardous pollutants for human health in the region, caused largely by human activities such as the use of fertilizers, septic tank leakage, and discharge of organic matter into the water.	[83]
4.	Semi-arid environment of Essaouira Basin, Morocco	The water was not suitable for human consumption as it contained excessive amounts of calcium, magnesium, sodium, potassium, chloride, sulphate, bicarbonate and nitrate, as well as total dissolved solids that exceed the World Health Organization's standards. Research on nitrate pollution revealed elevated levels, which was attributed to three factors: (i) high level of tourism in the Sidi Kaouki area, (ii) lack of a proper sewage system and wastewater treatment facility, and (iii) discharge of animal waste during watering.	[84]
5.	Manali, Northern India	The rise in tourism has led to an increase in water consumption, resulting in the deterioration of water quality. The key pollutants responsible were sewage and solid waste. The population growth and urbanization caused a surge in sewage production, which is further exacerbated by the absence of a functional sewage treatment facility. This untreated sewage was directly discharged into the river, which is even worse than the conventional disposal method of letting sewage and grey water seep through the soil. The water quality downstream generally exhibited lower values of variables like BOD, DO, and TC compared to upstream, which can be partly attributed to urbanization and tourism.	[4]
6.	Tianchi scenic area of Xinjiang, China	Tourism-related activities significantly degraded the quality of surface water.	[85]
7.	Potrero de los Funes River, San Luis, Argentina	The average values of E. coli through all the studied periods exceeded the reference values established by the international organisms for recreational waters due to enriched nutrient level in water.	[3]
8.	Lidder River in Kashmir Himalayas, India	During the tourist season, the levels of nutrients such as nitrate nitrogen, ammoniacal nitrogen, total phosphorus, orthophosphate phosphorus, and BOD in the river were found to be alarmingly high. Apart from the sewage produced by hotels, guest houses, and residential areas, agricultural runoff was also a contributing factor to this issue.	[8]
9.	Semi-arid Coastal Aquifers, South Africa	A good percentage of water was found to be polluted by heavy metals such as lead, cadmium, and iron. Children were found to be at a higher risk than adults, as their hazard quotients (HQ) and hazard index (HI) was relatively higher.	[9]
10.	Semi-arid region of South India	The range of nitrate content in groundwater was 17 to 120 mg/L, with 57% of the samples surpassing the allowable limit. Agriculture and the discharge of human and animal waste were identified as the main causes of nitrate enrichment in groundwater. Additionally, it was shown that children in the study region had non-carcinogenic risks total hazard index (HI) that were 1.38 and 1.15 times greater than those for men and women, respectively.	[86]

ministration and infrastructure, and the region's geopolitical significance are some of the elements contributing to Leh's urban growth trend [88]. It has been observed that after the formation of Ladakh as Union territory, the developmental work has taken place at a very high pace but at the same time that has also increased vulnerabilities, including physical, sociocultural, economic, environmental, and climate-related threats [89]. A study revealed that interstate migration has doubled 1971 to 2011 in the UT of Ladakh and Leh dominates in interstate migrants [90]. In 2012–2013, a study utilized geographic information systems (GIS) to map point sources of water pollution in Leh, along with medical data analysis and surveys of households and hotels [91]. The findings suggested a potential link between groundwater pollution and increased occurrences of diarrhoea in the area over the past decade. Moreover, with over 80% of water demand being met by unregulated groundwater extraction, there's concern about depletion surpassing recharge rates. The study proposed leveraging GIS for informed urban planning and advocates for a partially decentralized sewage system to conserve water resources in Leh [91]. The study on anthropogenic climate change in the Ladakh Himalayas revealed a significant increase in greenhouse gases (GHGs), black carbon (BC), and pollutants from vehicular traffic near glaciers. The rise in temperatures, attributed to the heightened levels of GHGs and pollutants, has accelerated glacier melting in the region. If this trend persists, Himalayan glaciers could vanish entirely, leading to profound effects on regional water supplies, hydrology, ecosystem services, and transboundary water management [92]. The study conducted in the Alata River Basin based on climate change projections indicated a consistent rise in annual mean temperatures throughout the century, coupled with a decrease in precipitation across all future scenarios. These changes are expected to result in increased snowmelt and higher discharge generation, especially in the beginning and middle of the century. Similarly, a research performed in Leh demonstrated a warming trend in the climate, accompanied by reduced precipitation during the current decade [34]. Hence, Ladakh, being one of the ecologically fragile environments, faces a looming threat of water scarcity due to climate change and escalating anthropogenic pressures.

Climate change scenario studies offer valuable insights for devising mitigation and adaptation strategies. It is widely acknowledged that the impacts of climate change, and consequently the strategies for adaptation, differ from one location to another, contingent upon hydrological, socio-economic, and geographical factors. This underscores the imperative for investigating climate change impacts at the local level [93]. While this situation rapidly reduces the amount of groundwater, it also negatively affects its quality. Salinization, one of the most important factors affecting the quality of groundwater, is a global problem that is difficult to reverse. Thus, research and studies on the salinization of groundwater are important and imperative [94]. Table 11 summarizes different indicators of urbanization and their impact on the Ladakh region [7, 10, 12–14, 38, 59, 62, 73–76, 95–105].

CONCLUSION AND FUTURE RECOMMENDATIONS

In summary, Ladakh's rapid urbanization and thriving tourism industry pose significant environmental challenges, particularly in terms of water availability and quality. Since its opening to tourism in 1974, Ladakh has witnessed a significant influx of visitors, with tourist numbers soaring from 527 initially to approximately 531,396 in 2022. This surge, nearly double the local population of Ladakh, has led to the conversion of agricultural land for hotel construction. Over the years, the conversion of agricultural land has escalated from 1% in 1969 to 8% in 2017. Consequently, there has been a noticeable decline in the rural population, as the economy shifts from agriculture-based to tourism-driven. The unregulated extraction of groundwater and the transition from dry toilets to water-intensive flush toilets have exacerbated water quality degradation. Reports indicate an increase in dissolved solids concentration over time, highlighting the environmental challenges arising from rapid tourism growth in Ladakh. Instead of relying solely on reactive measures to address the damage caused, it is crucial to implement preventive policies from the outset of the planning process. Sensible policies should be adopted to tackle the problems arising from the increasing tourism, such as educating tourists about the environment, implementing tourist taxes, promoting the use of compost toilets as an alternative to water-intensive flush toilets, and possibly regulating the number of tourists visiting the area. Efforts are needed to address these issues and ensure sustainable development in the region.

To ensure sustainable urbanization and tourism, it is essential to implement both short-term and long-term policies to conserve the limited water resources in the region. GIS can play a vital role in assessing water quality and promoting sustainable tourism development. By utilizing GIS, a versatile platform that integrates and analyses diverse information, stakeholders can gain a comprehensive understanding of water bodies. This will enable them to make well-informed decisions and effectively manage and preserve these resources for sustainable tourism [11]. Therefore, it is important to promote the use of GIS-based water quality assessment for sustainable tourism and urbanization.Further, it is crucial to extend studies beyond the Leh district in Ladakh and examine the impact of urbanization and tourism in other areas as well. Currently, most research has focused on Leh due to its accessibility by air, while other significant places such as Kargil have been overlooked.

The most challenging aspect of managing the water supply in the Ladakh region in the face of future climate change is predicting and preparing for the potential effects of global warming on precipitation and temperature patterns. In recent decades, Leh has experienced a rapid increase in temperature and unpredictable precipitation. The changing climate in the Leh region will have adverse and potentially irreversible impacts on both the natural environment and human activities [34]. Therefore, it is crucial for the administration to strictly implement measures to mitigate global warming, achieve the goals of 100% carbon neutrality, and preserve glaciers in the region. Encouraging the implementation of artificial glaciers

Table 11. Impact of urbanization on water quality with special reference to Ladakh

Indicators of urbanization	Reason	Impact	Reference
Enhanced constructional activities	Growing tourism industry, urban lifestyles, infrastructure development, administrative and geopolitical significance.	•Rapid expansion of housing settlements, encompassing former agricultural and barren lands. •The overall built-up area increased from 36 hectares in 1969 to 196 hectares in 2017. •Agricultural land lost to construction rose from 1% in 1969 to 8% in 2017.	[12, 13, 102]
Overcrowding		•Army and tourism in the floating population a significant factor contributing to urbanization in Leh Ladakh. •Census reports of India from 1980, 2001, and 2011, show a decline in the rural population and an enhanced urban population. •Leh town has been reported as the fastest urbanizing place in Ladakh. •Significant increase in tourism every year. In 2022 the tourist inflow increased 17 folds to 5,31,396 (Fig 6).	[7, 12–14, 59, 73–76, 102, 103]
Issue of access to safe water		•Unequal access to water resources leads to social and environmental changes, harming water quality and availability. •Increased amount of microplastic in Indus River water as compared to other major Rivers of India. •Groundwater found significant pollution due to the accumulation of Cr, Cd, Ni, Mn, Fe, and Cu. •Cd, As, and Pb found above the WHO's permissible limit in the Indus River, irrigation water, and stagnant water at various locations in Leh. •Higher levels of Mg, Na, K, Mn, Ca, Cl, S, and Al were found in the Indus River water collected near the city area of Leh as compared to previous studies with concentration of Al and alkalinity exceeding the limits prescribed by the WHO. •Anthropogenic activities and agricultural waste are the main factors affecting the water quality of the Indus River and the effects are more prominent during the summer season, indicating the impact of tourism on water quality. •The recent surge in urbanization and tourism is found to threaten the fragile environment, especially water availability, worsened by climate change. •Reports have uncovered bacterial contamination in the spring-fed water pipeline system serving the Chubi region of Leh. While spring water has historically been trusted for drinking in Ladakh, this contamination casts doubt on its reliability as a water source. •In the study, 75% of the samples of groundwater showed higher levels of turbidity, and 10% exceeded the desired range for EC and TDS. •Increased occurrences of diarrhea in the area over the past decade. Moreover, with over 80% of water demand being met by unregulated groundwater extraction, with concern about depletion surpassing recharge rates	[12, 14, 38, 59, 62, 74, 104]
Improved sanitation		In Leh town, there has been a notable shift from traditional dry sanitation to water-intensive flush toilets. Untreated grey and black water is disposed of in soak pits or septic tanks due to a partially functional seweage system, posing a serious threat to groundwater contamination.	[10, 74]
Increasing traffic issue		With the anticipated surge in tourism and population leading to increased vehicle traffic, air pollution is expected to rise. A study conducted near the national highway in Ladakh reveals a significant impact on glacier melting attributed to the increase in greenhouse gases (GHGs) and black carbon (BC) emissions.	[92, 105]

at the village level should also be promoted. The pressures of urbanization are expanding beyond Leh town to other parts of Ladakh, notably the Kargil district. Between 1965 and 2020, the built-up area increased over ninefolds, with the urban population of Kargil town soaring from 1681 in 1961 to 16,338 in 2011 [95]. This necessitates extending research efforts to encompass various towns and regions across Ladakh. Such studies can offer a deeper insight into hydrochemical dynamics and the effects of urbanization on water quality, facilitating informed decision-making and sustainable planning strategies for the entire region.

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DATA AVAILABILITY STATEMENT

The author confirm that the data that supports the findings of this study are available within the article. Raw data that support the finding of this study are available from the corresponding author, upon reasonable request.

CONFLICT OF INTEREST

The author declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

USE OF AI FOR WRITING ASSISTANCE

Not declared.

ETHICS

There are no ethical issues with the publication of this manuscript.

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APPENDICES

Appendix 1. Classification of water quality based on electrical conductivity [53]

Electrical conductivity (µS/cm)	Classification	Source of water
<1500	Permissible	Groundwater, River water and Freshwater lakes
1500–3000	Not permissible	Hot springs
>3000	Hazardous	Saline Lakes

Appendix 2. Classification of water quality based on total dissolved solids [53]

Total dissolved solids (mg/L)	Classification	Remarks
<1000	Fresh water type	Groundwater, River water and freshwater lakes
1000–10000	Brackish water type	Hot springs and Saline Lakes
10000–100000	Saline water type	–
>100000	Brine water type	–

Appendix 3. Classification of water quality based on total hardness [53]

Total hardness as $CaCO_3$ (mg/L)	Classification	Remarks
<75	Soft	Groundwater, River water and freshwater lakes
75–150	Moderately high	
150–300	Hard	Hot springs and saline lakes
>300	Very hard	Hot springs and saline lakes

Appendix 4. Classification on the basis of sodium percent [72]

Sodium percent	Suitability for irrigation	Remarks
<20	Excellent	None
20–40	Good	Most of the river water, glacial melts, ground water and freshwater lake fall under good to permissible limit.
40–60	Permissible	
60–80	Doubtful	Some ground water ample during tourist season are also in doubtful category.
>80	Unsuitable	Water from hot spring is unsuitable.