Supplementary Information (SI) for Environmental Science: Nano.

Supporting Information

Metal nanoparticles in glaciers: occurrence, transport, and implications for freshwater ecosystems

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Text S1. Chemicals and Materials.

An inductively coupled plasma multi-element standard solution (PerkinElmer Multi-Element Calibration Standard, containing Au, Ag, Cu, Ti, Al, Ce, and La, each at 10 mg/L in 5% HNO_3) was obtained from PerkinElmer (Waltham, USA). A spherical Au NPs dispersion (100 nm, βAu = 50.0 mg/L, number concentration of Au NPs = 5.71×109 particles per mL, coated with carboxylic acid) was also purchased from PerkinElmer (Waltham, USA). Hydrochloric acid (36.5%, 500 mL, SCR®) and nitric acid (69.0%, 2.5 L, EMPARTA® ACS) were purchased from HUSHI (Shanghai, China) and Merck (Darmstadt, Germany), respectively. All chemicals were of at least analytical grade and were verified for contamination by inductively coupled plasma mass spectrometry (ICP-MS) prior to use. Ultrapure water (with a resistivity of 18.2 MΩ·cm) was supplied by a Milli-Q® reference water purification system equipped with a 0.22 μm membrane filter from Merck (Milli-Q® IQ 7005, Darmstadt, Germany). All glassware was soaked in 5% (w/w) HNO_3 overnight and subsequently rinsed three times each with nitric acid and ultrapure water before use.

Text S2. Sample Collection and Pretreatment

Sample Collection

Sampling was conducted from July to August 2021 across five glaciers in the southern QTPs. Snowpack samples were collected from the surface layer at locations distant from trails, camps, and infrastructure to minimize local anthropogenic influence. Runoff samples were taken along flow paths from the glacier terminus, covering upstream, midstream, and downstream sections. At each site, at least three replicate water samples were collected.

To prevent contamination, operators wore nitrile gloves during sampling. Pre-cleaned polypropylene bottles (rinsed three times with methanol and Milli-Q water) were used for all samples. Approximately 100 mL of snow was collected directly into bottles and allowed to melt in the dark under laboratory conditions. Runoff water (about 200 mL per sample) was collected directly from the flow. Field blanks were prepared by exposing ultrapure water to ambient air at the sampling sites and handling it identically to the samples.

Sample Pretreatment

In the laboratory, each sample was divided into two aliquots: one for elemental analysis and one for single-particle analysis. The aliquot for elemental analysis was acidified to 3.25 % (w/w) with ultrapure nitric acid immediately after melting/filtration. The aliquot for particle analysis remained unacidified to avoid nanoparticle dissolution. All samples were filtered through 0.45 μm membrane filters prior to further processing.

For single-particle analysis, filtered samples were concentrated using ultrafiltration devices (Amicon Ultra, Millipore) with molecular-weight cut-offs of 10 kDa or 100 kDa to increase nanoparticle concentration. All pretreatment steps (filtration, ultrafiltration) were performed in parallel with procedural blanks consisting of ultrapure water treated identically to the samples.

Quality Assurance

Throughout the SP-ICP-MS analysis, instrument blanks (2 % HNO_3) were measured routinely to establish background signal levels. The limit of detection (LOD) for particle number concentration was defined as a signal-to-noise ratio of 3. No quantifiable signals for the target MNPs were observed in any procedural, or instrument blanks.

Text S3. Instrumental Analysis.

Seven elements and their corresponding MNPs (including Ti NPs, Al NPs, Cu NPs, La NPs, Ag NPs, Au NPs, and Ce NPs) were analyzed using both the standard mode and the single-particle (SP) mode of ICP-MS (NexION 2000, PerkinElmer, Waltham, USA) equipped with a MicroMist nebulizer (PerkinElmer, Waltham, USA). Argon 4.8 was used as the plasma gas. For the determination of the concentrations of Ti, Al, Cu, La, Ag, Au, and Ce in the samples, the integration time was set to 0.1 s, and ^{103}Rh was employed as the internal standard. For MNPs analysis, including concentration and size, the dwell time was set to 100 μs, and scan time was set to 100 s to generate 1.00×10^6 data points for each injection. The sample flow rate was 0.125 mL/min by gravimetrically calculation and ^{47}Ti, ^{27}Al, ^{63}Cu, ^{139}La, ^{107}Ag, ^{197}Au, and ^{140}Ce were selected as target masses. Transport efficiency was calculated using the AuNPs dispersion (100 nm, number concentration = 5.71×10^9 particles per mL). Calibration was performed with a dissolved multi-element standard solution (10.0 mg/L in 5% HNO_3), which was used to determine elemental intensity. Additional instrumental settings are provided in Table S12.

According to the principle of transforming raw pulse intensity into particle size proposed by Pace et al.,[1] we can figure out that when the particle size is too small, the pulse signal generated by the particle cannot be distinguished from the background signal, and the size of NPs cannot be quantified correctly. This phenomenon defines the size limit of detection (LOD_{size}) in the application of SP-ICP-MS. MNPs are assumed to be spherical in uniform density. The calculation for the LOD_{size} is as follows:

$$(1)\ D_{min} = \left(\frac{6\eta \times I_{Thre}}{k \times f_a \times \rho \times \pi}\right)^{1/3}$$

where η (%) is the transmission efficiency, I_{Thre} is the intensity threshold that can distinguish particle signal from background signal,[2] k (CPS/μg) is the slope of the calibration curve for ion standard solution, f_a is the mass fraction of the analyzed element in the MNPs, ρ (g/cm^3) is the density of the MNPs. When calculating LOD_{size} using the formular, a 5σ (σ being the standard deviation of the entire dataset corresponding to one sample) iterative algorithm criterion was applied to the parameter I_{Thre} to distinguish true particle events from background signal.[3]

According to the formular (1), it could be known that the LOD_{size} varies among different MNPs. In this study, the LOD_{size} of Ti NPs, Al NPs, Cu NPs, La NPs, Ag NPs, Au NPs, and Ce NPs were 9, 16, 12, 12, 15, 12 and 25 nm, respectively. MNPs smaller than the corresponding LOD_{size} cannot be reliably identified as NPs. In such cases, their concentrations were reported as “Not detected” (ND).

SP-ICP-MS cannot definitively distinguish or quantify between natural and anthropogenic nanoparticles. Achieving more precise source tracking will require advanced multi-dimensional fingerprinting techniques in future research, such as stable isotope analysis.[4]

Text S4. Culture of *Chlorella* sp.

Under sterile conditions, 50 mL of algal suspension was inoculated into a 250 mL conical flask sterilized by high temperature and pressure, and then mixed with an equal volume of autoclaved BG11 medium. Cultures were maintained in a light incubator at a light intensity of 22000 Lx and relative humidity of 80%. A light-to-dark cycle of 14 h/10 h was applied, and the position of the flasks in the incubator was randomly changed and gently shaken twice daily.

Text S5. Exposure Experiment.

This experiment was designed as a conservative, baseline hazard assessment of MNPs for freshwater phototrophs. Exposure parameters were grounded in environmental measurements. Exposure concentrations of MNPs were set at 1×, 100×, 10000×, and 1000000× the lowest detected concentrations. Generally, smaller MNPs of the same composition exhibit greater toxicity than larger ones.[5, 6] Therefore, exposure sizes were chosen to not exceed the actual average sizes of MNPs in glaciers. Specifically, 10 nm for Ag NPs, 20 nm for Au NPs, 30 nm for Cu NPs, and 40 nm for TiO_2 NPs. Additionally, because MNPs in glaciers coexist in specific proportional relationships, we conducted a composite exposure experiment based on the actual composition of MNPs measured in glaciers.

Chlorella sp. was employed under its optimal growth conditions during exposure. This approach serves two purposes: it addresses the difficulty of replicating the extreme supraglacial environment,[7-10] while establishing a precautionary effect baseline by minimizing confounding abiotic stress.[11] Specifically, *Chlorella* sp. was handled on a sterile workbench, and an initial concentration of 1×10^6 cells/mL[12] was transferred into six-well plates, with 5 mL of algal suspension per well. MNPs were centrifuged at 14,000 rpm, resuspended in BG11 medium, and subjected to 3 min of ultrasonication before addition to the wells, either individually or as a mixture. Each treatment group included 4 replicates. Following exposure, plates were maintained in a light incubator for 72 h. The algal suspension in each well was gently mixed twice daily using a pipette. Additional experimental details are provided in Table S2.

Text S6. Data Analysis.

For statistical comparison between two groups (e.g., exposure and control groups), data following a normal distribution pattern were analyzed using the two-sided t-test, while the Wilcoxon-Mann-Whitney nonparametric test was applied for non-normally distributed datasets. For comparisons involving more than two groups, One-Way ANOVA was used for normally distributed data and the Kruskal-Wallis test for non-normally distributed data. All statistical analyses were carried out using GraphPad Prism (v9.0, GraphPad Software Inc.), and in all tests, $p < 0.05$ was considered statistically significant.

Table S1 Water quality parameters of runoffs and altitude of snowpacks.

	Sample	Altitude (m)	pH	Temperature (T, ℃)	Flow Rate (m^3/h)	TOC (mg/L)	Conductivity (σ, μs/m)	DO (mg/L)
Parlung No. 4 (PL) glacier	Snowpack	4791	-	-	-	-	-	-
	Upstream	4720	8.59	1.2	4234	7.45	-	4.00
	Midstream	4688	8.67	0.3	4460	6.79	10.0	5.30
	Downstream	4620	8.60	-	-	6.02	-	-
Korchung Gangri (KG) glacier	Snowpack	5666	-	-	-	-	-	-
	Upstream	5500	8.59	3.1	6977	7.69	-	13.70
	Midstream	5503	8.67	1.7	7985	7.08	-	14.30
	Downstream	5567	8.54	2.5	3082	5.42	-	14.00
Qiangyong (QY) glacier	Snowpack	5191	-	-	-	-	-	-
	Upstream	4895	8.10	3.4	6887	5.84	-	-
	Midstream	-	8.09	3.9	5990	6.20	-	7.00
	Downstream	-	8.07	3.2	-	5.95	160.0	7.70
Rongbuk (RB) glacier	Snowpack	-	-	-	-	-	-	-
	Upstream	5171	8.60	2.3	4246	5.39	99.3	5.66
	Midstream	5154	8.64	3.8	2987	5.46	89.7	5.34
	Downstream	5145	8.47	5.6	3278	4.82	101.6	5.54
Rijie Cojia (RC) glacier	Snowpack	4918	-	-	-	-	-	-
	Upstream	5300	8.45	0.2	6444	6.23	180.0	12.70
	Midstream	-	8.34	2.6	3571	4.34	150.0	11.90
	Downstream	-	8.40	1.8	2088	4.24	160.0	11.90

Table S2 *Chlorella* sp. exposure experiment.

	Diameter(nm)	Concentration (ng/L)			
Ag NPs	10.0	1	100	10000	1000000
Au NPs	20.0	1	100	10000	1000000
Cu NPs	30.0	1	100	10000	1000000
TiO_2 NPs	40.0	10	10000	100000	10000000
Combined exposure of MNPs					
Ag NPs	10.0	1	100	10000	1000000
Au NPs	20.0	1	100	10000	1000000
Cu NPs	30.0	1	100	10000	1000000
TiO_2 NPs	40.0	10	10000	100000	10000000

Table S3 Average concentrations and diameters of 7 metal nanoparticles (MNPs) in 4 glacial snowpacks.

Analyte / Glaciers	Ag NPs		Al NPs		Au NPs		Ce NPs	
	Conc. (ng/L)	Diameter (nm)	Conc. (ng/L)	Diameter (nm)	Conc. (ng/L)	Diameter (nm)	Conc. (ng/L)	Diameter (nm)
KG	0.90 ± 0.45	11.99 ± 1.70	7.17 ± 0.68	101.31 ± 17.86	0.79 ± 0.01	15.90 ± 0.83	0.86 ± 0.31	18.07 ± 0.14
QY	2.95 ± 0.06	17.33 ± 1.51	10.02 ± 5.68	108.93 ± 5.68	0.42 ± 0.26	28.96 ± 0.83	2.05 ± 0.18	17.15 ± 0.14
RC	0.29 ± 0.07	10.97±0.08	12.06 ± 3.17	86.18 ± 2.88	1.00 ± 0.47	37.68 ± 0.76	1.69 ± 0.01	17.06 ± 0.07
PL	1.16 ± 0.82	12.68 ± 2.55	5.89 ± 2.79	104.19 ± 15.31	1.66 ± 0.08	15.24 ± 0.60	-	-

Analyte / Glaciers	Cu NPs		La NPs		Ti NPs	
	Conc. (ng/L)	Diameter (nm)	Conc. (ng/L)	Diameter (nm)	Conc. (ng/L)	Diameter (nm)
KG	0.62 ± 0.21	71.00 ± 5.58	1.55 ± 0.79	20.09 ± 0.11	9.30 ± 0.18	81.35 ± 1.28
QY	8.89 ± 1.10	19.24 ± 8.89	6.04 ± 0.19	20.25 ± 0.03	39.08 ± 20.47	60.53 ± 12.30
RC	2.76 ± 0.94	23.80 ± 0.44	11.00 ± 0.40	20.13 ± 0.40	333.34 ± 0.78	75.77 ± 0.13
PL	3.95 ± 0.88	27.83 ± 3.95	-	-	32.72 ± 7.12	84.22 ± 7.12

Table S4 The result of significant difference analysis in concentration of MNPs between snowpacks.

	Ti NPs	Al NPs	Cu NPs	La NPs	Ag NPs	Au NPs	Ce NPs
KG vs. QY	<0.0001	0.7265	0.0165	0.3617	0.8774	0.9991	0.9725
KG vs. RC	<0.0001	0.2864	0.8631	0.0044	0.9961	0.9998	0.9903
KG vs. PL	<0.0001	0.9661	0.6188	0.9421	0.9997	0.9889	0.9892
QY vs. RC	<0.0001	0.8789	0.1198	0.2743	0.7665	0.9966	0.9992
QY vs. PL	0.0995	0.4369	0.2777	0.1286	0.9143	0.9690	0.8774
RC vs. PL	<0.0001	0.1161	0.9725	0.0006	0.9889	0.9951	0.9266

Table S5 The result of significant difference analysis in mean size of MNPs between snowpacks.

	Ti NPs	Al NPs	Cu NPs	La NPs	Ag NPs	Au NPs	Ce NPs
KG vs. QY	<0.0001	0.1347	<0.0001	>0.9999	0.4243	0.0017	0.9937
KG vs. RC	0.3853	0.0002	<0.0001	>0.9999	0.9912	<0.0001	0.9917
KG vs. PL	0.8435	0.8428	<0.0001	<0.0001	0.9973	0.9976	<0.0001
QY vs. RC	0.0002	<0.0001	0.5611	>0.9999	0.2691	0.0660	>0.9999
QY vs. PL	<0.0001	0.5288	0.0721	<0.0001	0.5456	0.0009	<0.0001
RC vs. PL	0.0794	<0.0001	0.6572	<0.0001	0.9612	<0.0001	<0.0001

Table S6 Average concentrations and diameters of 7 metal nanoparticles (MNPs) in 5 glacial runoffs.

	Runoffs Direction	Ti NPs		Al NPs		Cu NPs		Ag NPs	
		Conc.(ng/L)	Diameter(nm)	Conc.(ng/L)	Diameter(nm)	Conc.(ng/L)	Diameter(nm)	Conc.(ng/L)	Diameter(nm)
RB	U: upstream	3304.8±84.6	131.7±0.45	4.92±1.28	119.04±2.8	4.91±1.76	56.35±1.43	0.63±0.08	10.9±0.22
	M: midstream	4177.1±39.28	143.15±0.08	5.67±2.14	118.96±0.04	0.4±0.17	43.8±0.11	1.13±0.65	9.65±0.48
	D: downstream	6947.15±35.95	149.38±0.0195	14.37±4.69	138.79±1.08	2.71±0.55	63.81±0.13	1.6±0.07	8.31±0.2
	Average	4809.68±1552.8	141.41±7.32	8.32±4.29	125.6±9.33	2.67±1.84	54.65±8.26	1.12±0.4	9.62±1.06
PL	U: upstream	353.33±0.1	74.97±0.1	9.9±0.26	106.54±4.32	5.8±0.01	42.91±5.8	6.18±0.4	12.79±0.38
	M: midstream	173.57±0.35	78.63±0.35	17.06±2.09	137.24±6.58	1.1±0.23	57.18±1.1	4.27±0.08	13.58±1.07
	D: downstream	463.48±0.02	80.85±0.34	5.22±2.78	105.14±5.42	1.8±0.22	57±0.06	3.68±0.07	12.78±0.16
	Average	330.13±119.49	78.15±2.42	10.72±4.87	116.31±14.81	2.9±2.07	52.36±6.68	4.71±1.07	13.05±0.38
KG	U: upstream	72.64±3.76	74.31±5.56	13.15±5.08	80.67±4.18	0.27±0.23	36.63±3.83	1.07±0.16	13.21±0.62
	M: midstream	98.61±3.72	74.66±4.22	12.49±5.26	83.43±0.36	0.37±0.06	42.36±0.49	1.44±0.27	12.7±0.05
	D: downstream	282.16±2.4	77.51±0.02	82.87±22.54	109.53±0.75	0.53±0.06	60.14±4.91	1.79±0.93	15.1±3.16
	Average	151.13±93.25	75.49±1.44	36.17±33.02	91.21±13	0.39±0.11	46.38±10.01	1.43±0.29	13.67±1.03
QY	U: upstream	58.44±1.51	48.35±0.36	53.11±1.6	71.83±1.6	4.75±0.06	43.51±4.75	2.57±0.47	17.33±1.42
	M: midstream	32.92±0.46	49.86±0.35	103.86±7.63	53.44±7.63	10.65±1.8	41.2±10.65	2.22±0.33	13.27±0.06
	D: downstream	24.6±0.55	59.73±0.46	99.72±8.46	78.81±8.46	8.53±1.1	45.88±8.53	3.56±0.98	15.58±0.81
	Average	38.65±14.4	52.65±5.05	85.56±23.01	68.03±10.7	7.98±2.44	43.53±1.91	2.78±0.57	15.39±1.66

RC	U: upstream	51.55±5.38	74.37±6.6	9.18±2.14	125.52±14.88	0.72±0.44	51.67±4.91	0.65±0.32	9.18±1.39
	M: midstream	-	-	-	-	-	-	-	-
	D: downstream	439.81±0.75	88.19±0.21	8.59±1.43	84.25±3.74	0.55±0.14	37.57±1.06	0.77±0.43	10.45±3.19
	Average	245.68±194.13	81.28±6.91	8.88±0.3	104.89±20.63	0.64±0.08	44.62±7.05	0.71±0.06	9.82±0.64

Table S6 continued

	Runoffs Direction	Au NPs		Ce NPs		La NPs	
		Conc.(ng/L)	Diameter(nm)	Conc.(ng/L)	Diameter(nm)	Conc.(ng/L)	Diameter(nm)
RB	U: upstream	0.47±0.06	42.5±0.31	0.14±0.04	18.05±2.31	0.2±0.05	20.1±0.31
	M: midstream	0.16±0.1	37.5±2.06	0.5±0.04	18.41±0.14	0.36±0.14	20.22±0.01
	D: downstream	1.16±0.06	40.65±0.37	1.96±0.03	29.96±0.25	4.44±0.35	20.15±0.2
	Average	0.6±0.42	40.22±2.06	0.87±0.78	22.14±5.53	1.67±1.96	20.16±0.05
PL	U: upstream	0.72±0.01	15.34±1.66	1.34±0.2	17.09±1.34	0.9±0.38	20.06±6.18
	M: midstream	0.6±0.17	13.5±0.72	1.32±0.07	17.1±1.32	1.1±0.07	20.14±4.27
	D: downstream	0.87±0.27	15.24±0.6	2.03±0.25	17.1±2.03	1.42±0.1	20.13±3.68
	Average	0.73±0.11	14.7±0.85	1.57±0.33	17.1±0.01	1.14±0.21	20.11±0.04
KG	U: upstream	1.05±0.03	15.48±0.12	3.88±0.29	21.94±0.25	1.66±0.11	20.02±0.03
	M: midstream	1.6±0.12	15.19±1.73	1.21±0.37	17.09±0.11	4.16±1.13	20.11±0.2
	D: downstream	1.06±0.03	15.28±2.71	3.13±0.95	17.16±0.01	4.39±1.26	20.12±0.02
	Average	1.23±0.26	15.32±0.12	2.74±1.12	18.73±2.27	3.4±1.24	20.08±0.04

QY	U: upstream	4.55±0.31	38.68±0.12	1.28±0.22	17.17±0.5	1.13±0.19	20.3±0.2
	M: midstream	0.88±0.37	27.65±1.73	0.37±0.11	18.44±1.96	0.79±0.37	20.13±0.36
	D: downstream	3.96±0.06	36.26±2.71	1.89±0.28	17.14±0.61	1.36±0.35	27.98±0.35
	Average	3.13±1.61	34.2±4.74	1.18±0.62	17.59±0.61	1.09±0.23	22.81±3.66
RC	U: upstream	0.28±0.15	36±1.01	0±0	0±0	8.13±0.4	20.25±0.52
	M: midstream	-	-	-	-	-	-
	D: downstream	0.53±0.48	44.63±7.2	2.02±0.11	17.13±0.07	0.47±0.35	20.07±0.31
	Average	0.41±0.13	40.31±4.31	2.02±0	17.13±0	4.3±3.83	20.16±0.09

Table S7 The result of significant difference analysis in concentration of MNPs between runoffs.

	Ti NPs	Al NPs	Cu NPs	La NPs	Ag NPs	Au NPs	Ce NPs
PL vs. KG	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	0.6744	0.0210
PL vs. QY	<0.0001	<0.0001	<0.0001	>0.9999	<0.0001	0.9170	0.8491
PL vs. RC	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	0.7579
PL vs. RB	<0.0001	<0.0001	0.9752	0.6422	<0.0001	0.9969	0.3630
KG vs. QY	<0.0001	<0.0001	<0.0001	<0.0001	0.0050	0.1973	0.0007
KG vs. RC	<0.0001	<0.0001	0.9678	0.1359	0.3236	<0.0001	0.3295
KG vs. RB	<0.0001	<0.0001	<0.0001	0.0001	0.9255	0.4537	<0.0001
QY vs. RC	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	0.1853
QY vs. RB	<0.0001	<0.0001	<0.0001	0.5655	0.0003	0.9876	0.9263
RC vs. RB	<0.0001	0.5841	<0.0001	<0.0001	0.8156	<0.0001	0.0251

Table S8 The result of significant difference analysis in mean size of MNPs between runoffs.

	Ti NPs	Al NPs	Cu NPs	La NPs	Ag NPs	Au NPs	Ce NPs
PL vs. KG	<0.0001	0.1746	0.9818	>0.9999	0.9233	<0.0001	0.7448
PL vs. QY	<0.0001	<0.0001	0.2774	>0.9999	0.8677	<0.0001	0.9243
PL vs. RC	<0.0001	<0.0001	0.0636	0.9689	0.6382	0.5995	0.8095
PL vs. RB	<0.0001	<0.0001	0.1187	>0.9999	>0.9999	>0.9999	0.7503
KG vs. QY	0.9685	<0.0001	0.6044	>0.9999	0.9999	0.9999	0.9950
KG vs. RC	<0.0001	<0.0001	0.2174	0.9669	0.9802	<0.0001	>0.9999
KG vs. RB	0.9440	0.0530	0.3439	>0.9999	0.9371	<0.0001	>0.9999
QY vs. RC	<0.0001	<0.0001	0.9600	0.9657	0.9938	0.0001	0.9987
QY vs. RB	0.6357	0.0112	0.9933	>0.9999	0.8868	<0.0001	0.9954
RC vs. RB	<0.0001	<0.0001	0.9990	0.9690	0.6675	0.5847	>0.9999

Table S9-1 The result of significant difference analysis in concentration of MNPs between snowpacks and runoffs.

	Al NPs	Ti NPs	Cu NPs	Ag NPs	La NPs	Ce NPs	Au NPs
PL	0.3143	0.0445	0.5613	0.8471	-	-	0.0022
KG	0.1143	0.1340	0.1904	0.1979	0.1655	0.1149	0.1041
QY	0.0381	0.9792	0.6654	0.7156	-	0.1629	0.1099
RC	0.8000	0.5885	0.0860	0.0223	0.1330	-	0.2262

Table S9-2 The result of significant difference analysis in diameter of MNPs between snowpacks and runoffs.

	Al NPs	Ti NPs	Cu NPs	Ag NPs	La NPs	Ce NPs	Au NPs
PL	0.8381	0.0257	0.0667	0.8471	-	-	0.6667
KG	0.4762	0.0681	0.3143	0.4884	0.8175	0.3635	0.0667
QY	0.0095	0.1251	0.0084	0.1143	-	0.0584	0.0667
RC	0.2	0.05	0.0667	0.8286	0.0667	0.6667	0.4667

Table S10 Average concentrations 7 metal elements in 4 glacial snowpacks.

	Ag Conc.(ng/L)	Al Conc.(ng/L)	Au Conc.(ng/L)	Ce Conc.(ng/L)	Cu Conc.(ng/L)	La Conc.(ng/L)	Ti Conc.(ng/L)
KG	3.64±0.12	4235.33±955.1	0.79±0.06	2.37±0.37	240.18±44.07	2.28±0.11	779.26±1.34
QY	15.27±1.71	10921.11±372.72	0.42±0.26	6.43±0.5	246.52±24.13	10.51±0.2	877.83±5.05
RC	2.72±0.61	7035.2±214.31	1±0.47	5.27±2.31	438.41±2.76	14.4±0.35	2030.18±1.31
PL	4.15±1.22	8190.73±51.81	1.66±0.47	-	190.95±3.95	-	817.85±8.72

Table S11-1 Correlation analyses between the concentration and size of MNPs and water chemical parameters or element concentration.

r	pH	T (℃)	Flow Rate	TOC	σ	DO	Ti -N	Ti -D	Al -N	Al -D
pH	1.000	-0.371	-0.329	0.279	-0.713	0.021	0.361	0.252	-0.069	0.251
T (℃)	-0.371	1.000	0.190	-0.343	0.021	-0.218	-0.552	-0.616	0.646	-0.656
Flow Rate	-0.329	0.190	1.000	0.232	0.723	0.615	-0.823	-0.649	-0.097	-0.187
TOC	0.279	-0.343	0.232	1.000	-0.428	-0.011	0.270	0.383	-0.421	0.583
σ	-0.713	0.021	0.723	-0.428	1.000	0.786	-0.751	-0.459	-0.029	0.134
DO	0.021	-0.218	0.615	-0.011	0.786	1.000	-0.418	-0.168	-0.476	0.448
Ti -N	0.361	-0.552	-0.823	0.270	-0.751	-0.418	1.000	0.920	-0.326	0.560
Ti -D	0.252	-0.616	-0.649	0.383	-0.459	-0.168	0.920	1.000	-0.538	0.677
Al -N	-0.069	0.646	-0.097	-0.421	-0.029	-0.476	-0.326	-0.538	1.000	-0.558
Al -D	0.251	-0.656	-0.187	0.583	0.134	0.448	0.560	0.677	-0.558	1.000
Cu -N	0.449	0.503	-0.141	-0.091	-0.257	-0.399	-0.104	-0.337	0.661	-0.488
Cu -D	0.180	-0.252	-0.285	0.294	0.389	0.205	0.458	0.426	-0.066	0.741
Ag -N	0.339	0.370	0.388	0.256	-0.264	0.462	-0.294	-0.363	0.138	0.018
Ag-D	-0.198	0.670	0.311	-0.231	-0.024	-0.224	-0.648	-0.749	0.622	-0.562
Au -N	-0.023	0.548	-0.186	-0.433	-0.104	-0.395	-0.244	-0.477	0.530	-0.493
Au -D	0.413	-0.356	-0.724	-0.283	-0.164	-0.458	0.479	0.396	0.000	0.017
Ce -N	-0.628	0.469	0.189	-0.360	0.335	0.226	-0.155	-0.153	0.101	-0.145
Ce -D	0.049	0.446	-0.495	-0.040	-0.553	-0.353	0.551	0.401	0.040	-0.028
La -N	-0.395	-0.145	0.101	-0.002	0.658	0.217	0.013	-0.023	-0.058	0.330
La -D	0.024	0.588	-0.144	-0.363	-0.104	-0.273	-0.153	-0.237	0.536	-0.241
T-Ti	0.398	-0.588	-0.741	0.319	-0.731	-0.407	0.981	0.939	-0.349	0.557
T-Al	0.311	-0.621	-0.675	0.116	0.038	0.232	0.912	0.873	-0.473	0.774
T-Cu	-0.452	0.136	0.206	-0.120	0.398	-0.070	-0.227	-0.206	-0.127	-0.263
T-Ag	0.085	0.478	-0.220	0.077	-0.477	-0.672	0.042	-0.106	0.587	-0.246
T-Au	0.197	0.162	-0.430	-0.127	-0.659	-0.515	0.098	-0.133	0.353	-0.282
T-Ce	-0.103	0.266	-0.366	-0.151	0.728	0.442	0.502	0.328	-0.008	0.427

Table S11-1 Continued

r	Cu -N	Cu -D	Ag -N	Ag-D	Au -N	Au -D	Ce -N	Ce -D	La -N	La -D
pH	0.449	0.180	0.339	-0.198	-0.023	0.413	-0.628	0.049	-0.395	0.024
T (℃)	0.503	-0.252	0.370	0.670	0.548	-0.356	0.469	0.446	-0.145	0.588
Flow Rate	-0.141	-0.285	0.388	0.311	-0.186	-0.724	0.189	-0.495	0.101	-0.144
TOC	-0.091	0.294	0.256	-0.231	-0.433	-0.283	-0.360	-0.040	-0.002	-0.363
σ	-0.257	0.389	-0.264	-0.024	-0.104	-0.164	0.335	-0.553	0.658	-0.104
DO	-0.399	0.205	0.462	-0.224	-0.395	-0.458	0.226	-0.353	0.217	-0.273
Ti -N	-0.104	0.458	-0.294	-0.648	-0.244	0.479	-0.155	0.551	0.013	-0.153
Ti -D	-0.337	0.426	-0.363	-0.749	-0.477	0.396	-0.153	0.401	-0.023	-0.237
Al -N	0.661	-0.066	0.138	0.622	0.530	0.000	0.101	0.040	-0.058	0.536
Al -D	-0.488	0.741	0.018	-0.562	-0.493	0.017	-0.145	-0.028	0.330	-0.241
Cu -N	1.000	-0.153	0.375	0.348	0.408	0.200	-0.319	0.114	-0.363	0.467
Cu -D	-0.153	1.000	0.054	-0.197	-0.173	-0.035	-0.037	0.109	0.358	-0.081
Ag -N	0.375	0.054	1.000	0.439	0.210	-0.500	0.067	0.079	-0.309	0.225
Ag-D	0.348	-0.197	0.439	1.000	0.725	-0.374	0.328	0.013	-0.291	0.349
Au -N	0.408	-0.173	0.210	0.725	1.000	0.172	0.161	0.114	-0.112	0.597
Au -D	0.200	-0.035	-0.500	-0.374	0.172	1.000	-0.419	-0.009	-0.058	0.203
Ce -N	-0.319	-0.037	0.067	0.328	0.161	-0.419	1.000	0.447	-0.031	0.082
Ce -D	0.114	0.109	0.079	0.013	0.114	-0.009	0.447	1.000	-0.452	-0.026
La -N	-0.363	0.358	-0.309	-0.291	-0.112	-0.058	-0.031	-0.452	1.000	-0.093
La -D	0.467	-0.081	0.225	0.349	0.597	0.203	0.082	-0.026	-0.093	1.000
T-Ti	-0.150	0.369	-0.337	-0.678	-0.288	0.517	-0.220	0.471	-0.021	-0.154
T-Al	-0.234	0.661	-0.176	-0.676	-0.329	0.396	-0.108	0.400	0.139	-0.223
T-Cu	-0.309	-0.304	-0.252	-0.013	0.082	-0.165	-0.101	-0.148	0.348	-0.172
T-Ag	0.460	0.036	0.137	0.587	0.733	0.133	0.154	0.301	-0.286	0.723
T-Au	0.185	-0.266	0.044	0.450	0.754	0.342	-0.051	0.088	-0.120	0.510
T-Ce	-0.208	0.544	-0.021	-0.248	0.057	0.086	0.435	0.458	0.437	0.040

Table S11-1 Continued

r	T-Ti	T-Al	T-Cu	T-Ag	T-Au	T-Ce	T-La
pH	0.398	0.311	-0.452	0.085	0.197	-0.103	-0.088
T (℃)	-0.588	-0.621	0.136	0.478	0.162	0.266	0.252
Flow Rate	-0.741	-0.675	0.206	-0.220	-0.430	-0.366	-0.089
TOC	0.319	0.116	-0.120	0.077	-0.127	-0.151	-0.432
σ	-0.731	0.038	0.398	-0.477	-0.659	0.728	0.398
DO	-0.407	0.232	-0.070	-0.672	-0.515	0.442	0.381
Ti -N	0.981	0.912	-0.227	0.042	0.098	0.502	-0.238
Ti -D	0.939	0.873	-0.206	-0.106	-0.133	0.328	-0.387
Al -N	-0.349	-0.473	-0.127	0.587	0.353	-0.008	0.243
Al -D	0.557	0.774	-0.263	-0.246	-0.282	0.427	0.110
Cu -N	-0.150	-0.234	-0.309	0.460	0.185	-0.208	0.071
Cu -D	0.369	0.661	-0.304	0.036	-0.266	0.544	0.353
Ag -N	-0.337	-0.176	-0.252	0.137	0.044	-0.021	0.469
Ag-D	-0.678	-0.676	-0.013	0.587	0.450	-0.248	0.431
Au -N	-0.288	-0.329	0.082	0.733	0.754	0.057	0.585
Au -D	0.517	0.396	-0.165	0.133	0.342	0.086	-0.171
Ce -N	-0.220	-0.108	-0.101	0.154	-0.051	0.435	0.265
Ce -D	0.471	0.400	-0.148	0.301	0.088	0.458	-0.165
La -N	-0.021	0.139	0.348	-0.286	-0.120	0.437	0.344
La -D	-0.154	-0.223	-0.172	0.723	0.510	0.040	0.492
T-Ti	1.000	0.750	-0.204	0.080	0.196	0.391	-0.334
T-Al	0.750	1.000	-0.336	-0.245	-0.320	0.570	0.195
T-Cu	-0.204	-0.336	1.000	-0.226	0.070	-0.067	-0.156
T-Ag	0.080	-0.245	-0.226	1.000	0.695	-0.006	0.010
T-Au	0.196	-0.320	0.070	0.695	1.000	-0.074	0.120
T-Ce	0.391	0.570	-0.067	-0.006	-0.074	1.000	0.304

Table S11-2 Correlation analyses between the concentration and size of MNPs and water chemical parameters or element concentration.

p	pH	T (℃)	Flow Rate	TOC	σ	DO	Ti -N	Ti -D	Al -N	Al -D
pH	0.000	0.191	0.231	0.314	0.047	0.945	0.205	0.385	0.814	0.388
T (℃)	0.191	0.000	0.516	0.230	0.961	0.474	0.050	0.025	0.017	0.015
Flow Rate	0.231	0.516	0.000	0.405	0.043	0.025	0.000	0.012	0.740	0.523
TOC	0.314	0.230	0.405	0.000	0.290	0.972	0.351	0.177	0.134	0.029
σ	0.047	0.961	0.043	0.290	0.000	0.021	0.052	0.301	0.950	0.774
DO	0.945	0.474	0.025	0.972	0.021	0.000	0.176	0.601	0.117	0.144
Ti -N	0.205	0.050	0.000	0.351	0.052	0.176	0.000	0.000	0.255	0.037
Ti -D	0.385	0.025	0.012	0.177	0.301	0.601	0.000	0.000	0.047	0.008
Al -N	0.814	0.017	0.740	0.134	0.950	0.117	0.255	0.047	0.000	0.038
Al -D	0.388	0.015	0.523	0.029	0.774	0.144	0.037	0.008	0.038	0.000
Cu -N	0.108	0.080	0.630	0.758	0.578	0.199	0.723	0.239	0.010	0.076
Cu -D	0.539	0.407	0.323	0.308	0.388	0.522	0.100	0.129	0.824	0.002
Ag -N	0.236	0.213	0.170	0.376	0.568	0.130	0.307	0.202	0.637	0.951
Ag-D	0.496	0.012	0.280	0.426	0.960	0.485	0.012	0.002	0.017	0.036
Au -N	0.937	0.053	0.524	0.122	0.824	0.204	0.400	0.085	0.051	0.073
Au -D	0.142	0.232	0.003	0.328	0.726	0.134	0.083	0.161	1.000	0.953
Ce -N	0.016	0.106	0.518	0.206	0.462	0.480	0.597	0.601	0.731	0.622
Ce -D	0.869	0.127	0.072	0.891	0.198	0.260	0.041	0.156	0.892	0.925
La -N	0.162	0.635	0.732	0.996	0.108	0.499	0.966	0.937	0.844	0.250
La -D	0.935	0.034	0.623	0.203	0.824	0.391	0.601	0.415	0.048	0.406
T-Ti	0.142	0.027	0.002	0.247	0.039	0.168	0.000	0.000	0.221	0.039
T-Al	0.260	0.018	0.006	0.681	0.929	0.445	0.000	0.000	0.087	0.001
T-Cu	0.090	0.643	0.461	0.669	0.329	0.819	0.436	0.480	0.665	0.363
T-Ag	0.763	0.084	0.431	0.785	0.232	0.012	0.887	0.719	0.027	0.396
T-Au	0.500	0.579	0.125	0.666	0.076	0.072	0.750	0.664	0.237	0.350
T-Ce	0.714	0.358	0.180	0.591	0.041	0.130	0.067	0.252	0.980	0.127

Table S11-2 Continued

p	Cu -N	Cu -D	Ag -N	Ag-D	Au -N	Au -D	Ce -N	Ce -D	La -N	La -D
pH	0.108	0.539	0.236	0.496	0.937	0.142	0.016	0.869	0.162	0.935
T (℃)	0.080	0.407	0.213	0.012	0.053	0.232	0.106	0.127	0.635	0.034
Flow Rate	0.630	0.323	0.170	0.280	0.524	0.003	0.518	0.072	0.732	0.623
TOC	0.758	0.308	0.376	0.426	0.122	0.328	0.206	0.891	0.996	0.203
σ	0.578	0.388	0.568	0.960	0.824	0.726	0.462	0.198	0.108	0.824
DO	0.199	0.522	0.130	0.485	0.204	0.134	0.480	0.260	0.499	0.391
Ti -N	0.723	0.100	0.307	0.012	0.400	0.083	0.597	0.041	0.966	0.601
Ti -D	0.239	0.129	0.202	0.002	0.085	0.161	0.601	0.156	0.937	0.415
Al -N	0.010	0.824	0.637	0.017	0.051	1.000	0.731	0.892	0.844	0.048
Al -D	0.076	0.002	0.951	0.036	0.073	0.953	0.622	0.925	0.250	0.406
Cu -N	0.000	0.602	0.187	0.222	0.148	0.493	0.267	0.697	0.203	0.092
Cu -D	0.602	0.000	0.854	0.499	0.554	0.905	0.900	0.712	0.209	0.784
Ag -N	0.187	0.854	0.000	0.116	0.472	0.068	0.820	0.789	0.282	0.439
Ag-D	0.222	0.499	0.116	0.000	0.003	0.188	0.252	0.964	0.313	0.221
Au -N	0.148	0.554	0.472	0.003	0.000	0.557	0.582	0.697	0.704	0.024
Au -D	0.493	0.905	0.068	0.188	0.557	0.000	0.136	0.977	0.844	0.486
Ce -N	0.267	0.900	0.820	0.252	0.582	0.136	0.000	0.109	0.917	0.780
Ce -D	0.697	0.712	0.789	0.964	0.697	0.977	0.109	0.000	0.104	0.928
La -N	0.203	0.209	0.282	0.313	0.704	0.844	0.917	0.104	0.000	0.751
La -D	0.092	0.784	0.439	0.221	0.024	0.486	0.780	0.928	0.751	0.000
T-Ti	0.609	0.194	0.238	0.008	0.318	0.058	0.450	0.089	0.943	0.598
T-Al	0.420	0.010	0.548	0.008	0.251	0.161	0.713	0.157	0.636	0.443
T-Cu	0.283	0.290	0.384	0.964	0.781	0.572	0.732	0.613	0.223	0.557
T-Ag	0.098	0.903	0.641	0.027	0.003	0.651	0.599	0.296	0.322	0.003
T-Au	0.544	0.379	0.886	0.123	0.003	0.253	0.869	0.775	0.697	0.075
T-Ce	0.475	0.044	0.944	0.393	0.846	0.769	0.120	0.099	0.119	0.892

Table S11-2 Continued

p	T-Ti	T-Al	T-Cu	T-Ag	T-Au	T-Ce	T-La
pH	0.142	0.260	0.090	0.763	0.500	0.714	0.756
T (℃)	0.027	0.018	0.643	0.084	0.579	0.358	0.384
Flow Rate	0.002	0.006	0.461	0.431	0.125	0.180	0.751
TOC	0.247	0.681	0.669	0.785	0.666	0.591	0.108
σ	0.039	0.929	0.329	0.232	0.076	0.041	0.329
DO	0.168	0.445	0.819	0.012	0.072	0.130	0.198
Ti -N	0.000	0.000	0.436	0.887	0.750	0.067	0.412
Ti -D	0.000	0.000	0.480	0.719	0.664	0.252	0.172
Al -N	0.221	0.087	0.665	0.027	0.237	0.980	0.402
Al -D	0.039	0.001	0.363	0.396	0.350	0.127	0.708
Cu -N	0.609	0.420	0.283	0.098	0.544	0.475	0.810
Cu -D	0.194	0.010	0.290	0.903	0.379	0.044	0.215
Ag -N	0.238	0.548	0.384	0.641	0.886	0.944	0.091
Ag-D	0.008	0.008	0.964	0.027	0.123	0.393	0.124
Au -N	0.318	0.251	0.781	0.003	0.003	0.846	0.028
Au -D	0.058	0.161	0.572	0.651	0.253	0.769	0.559
Ce -N	0.450	0.713	0.732	0.599	0.869	0.120	0.359
Ce -D	0.089	0.157	0.613	0.296	0.775	0.099	0.573
La -N	0.943	0.636	0.223	0.322	0.697	0.119	0.229
La -D	0.598	0.443	0.557	0.003	0.075	0.892	0.074
T-Ti	0.000	0.001	0.466	0.777	0.501	0.150	0.224
T-Al	0.001	0.000	0.221	0.378	0.265	0.027	0.487
T-Cu	0.466	0.221	0.000	0.418	0.813	0.813	0.580
T-Ag	0.777	0.378	0.418	0.000	0.006	0.983	0.973
T-Au	0.501	0.265	0.813	0.006	0.000	0.801	0.682
T-Ce	0.150	0.027	0.813	0.983	0.801	0.000	0.270

Note: N**-** represents the concentration, D**-** represents the mean size, T**-** represents the concentration of elements.

Table S12 Operating parameters of SP-ICP-MS for measurement of MNPs.

Parameter	Operation Setting
Cell	Standard/ Ammonia DRC
Reference	100 nm,5.71E5parts/mL,AuNPs
ICP RF Power	1.60E3
Nebulizer Gas Flow	1.08
Sample Flow Rate	0.125 mL/min
Dwell Time	100 μs
Scan Time	100 s
Transport Efficiency	6.50~8.50 %
Mass Monitored	^{197}Au, ^{107}Ag, ^{63}Cu, ^{47}Ti, ^{27}Al, ^{140}Ce and ^{139}La
Density of nPb	11.3 g/cm^3
RPq	0.500

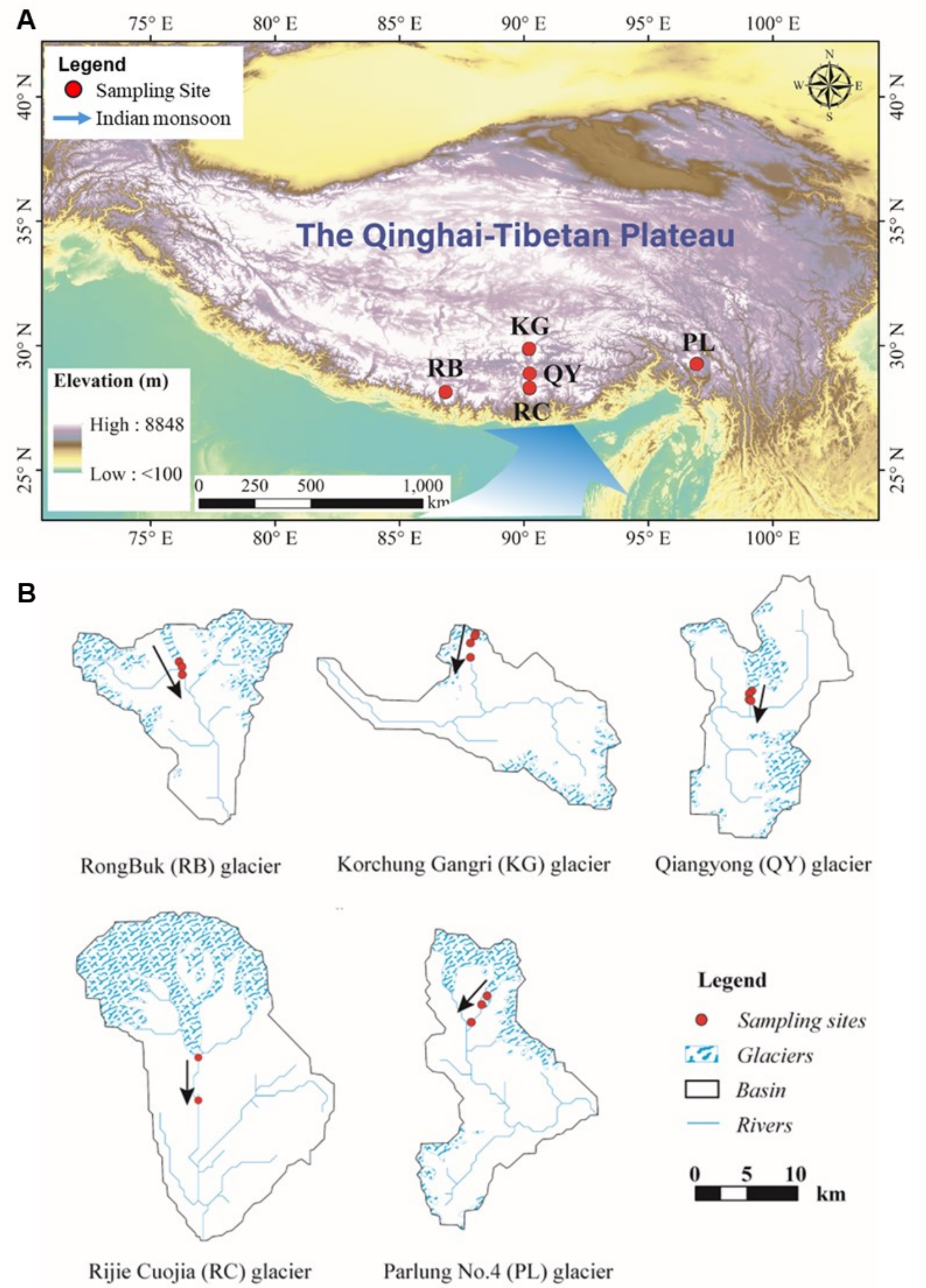

Figure S1. (A) Study area and sampling sites. Red dots represent the locations of sampling glaciers on the Qinghai-Tibetan Plateau (QTP), including the Rongbuk (RB), Qiangyong (QY), Rijie Cojia (RC), Korchung Gangri (KG) and Parlung No. 4 (PL) glacier. (B) Sampling sites in runoff from five glaciers. The three red dots on each local map represent the up-, mid-, and downstream of runoffs, and the arrows represent the direction of runoffs.

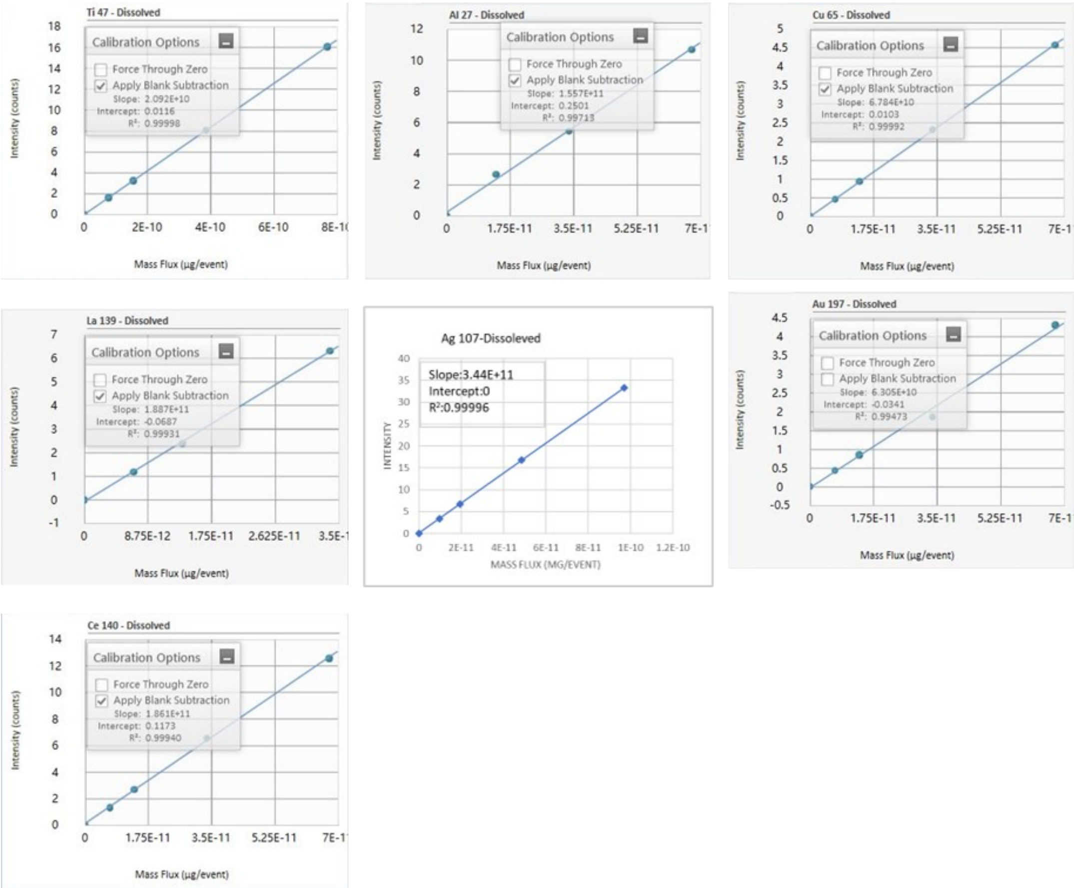

Figure S2. Calibrations of MNPs.

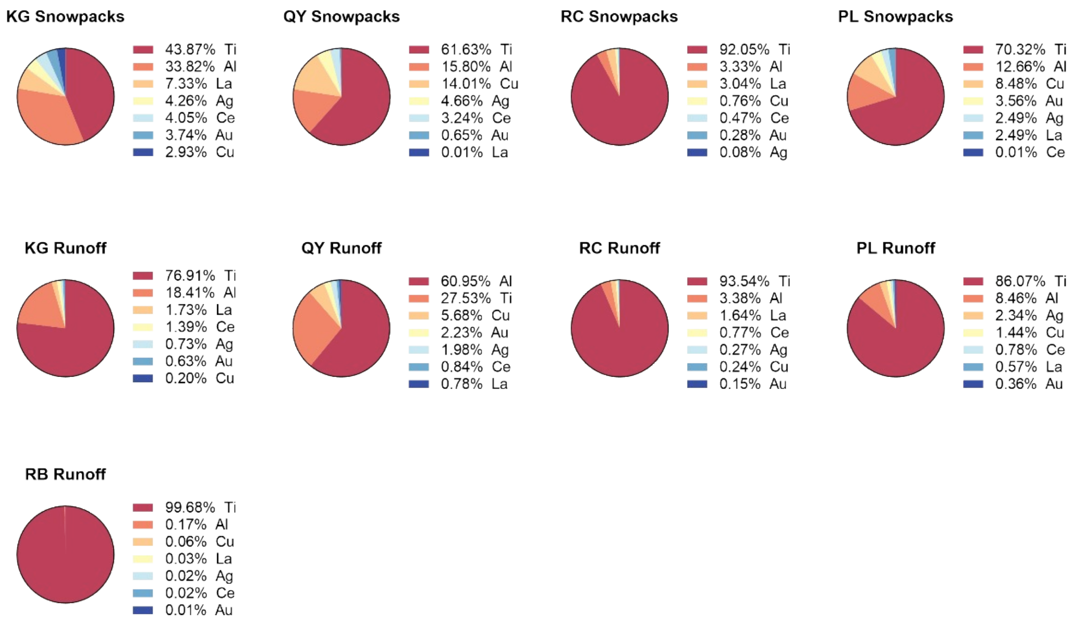

Figure S3. Compositions of 7 MNPs in glacial snowpacks and runoffs.

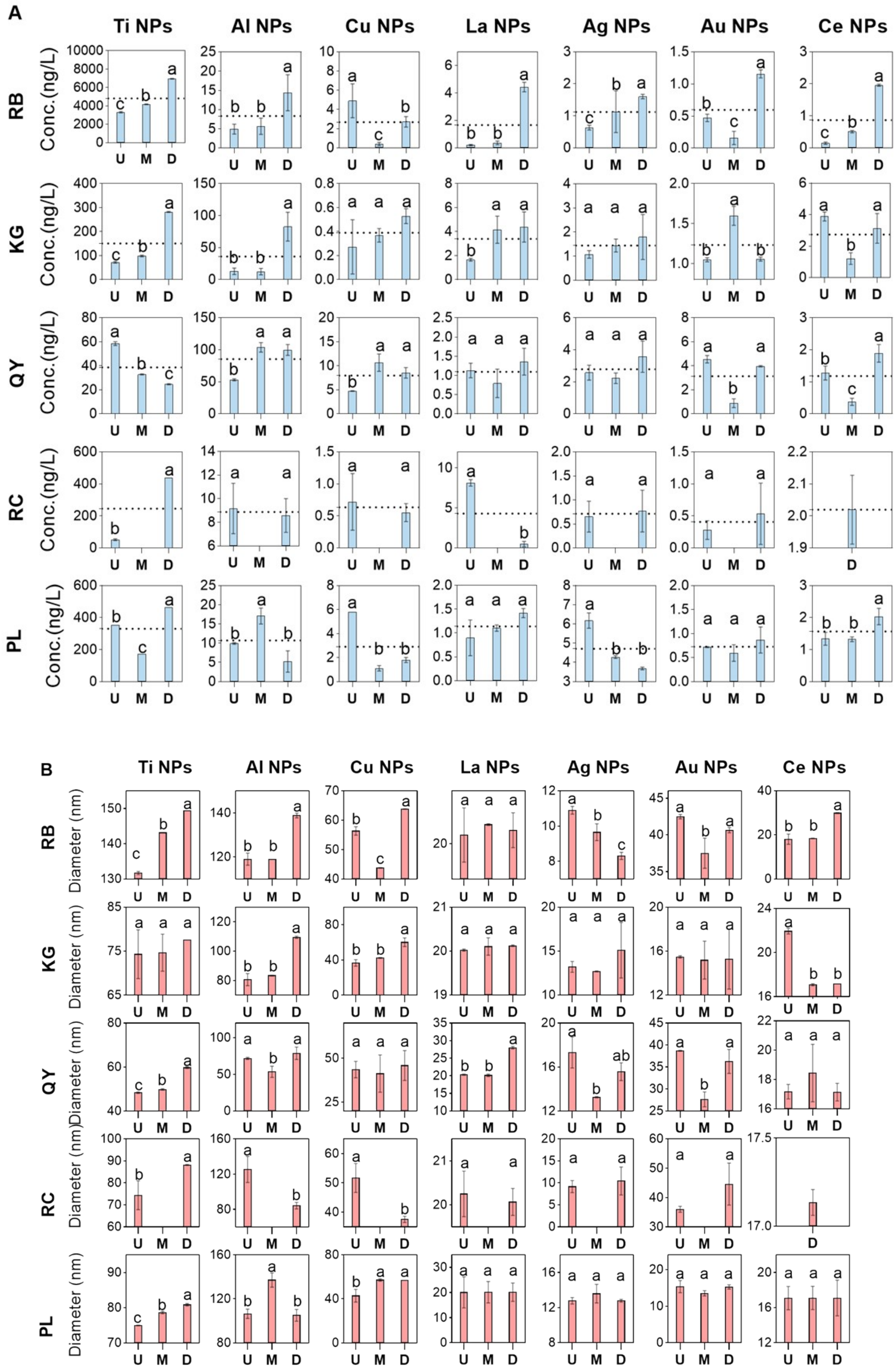

Figure S4. (A) Concentrations and (B) sizes of MNPs in glacial runoffs from upstream to downstream sites. **U**, **M**, and **D** represent the upstream, midstream, and downstream sampling sites, respectively. Low case letters above the bars denote statistically significant differences between groups (one-way ANOVA, p < 0.05). Groups sharing the same letter are not significantly different.

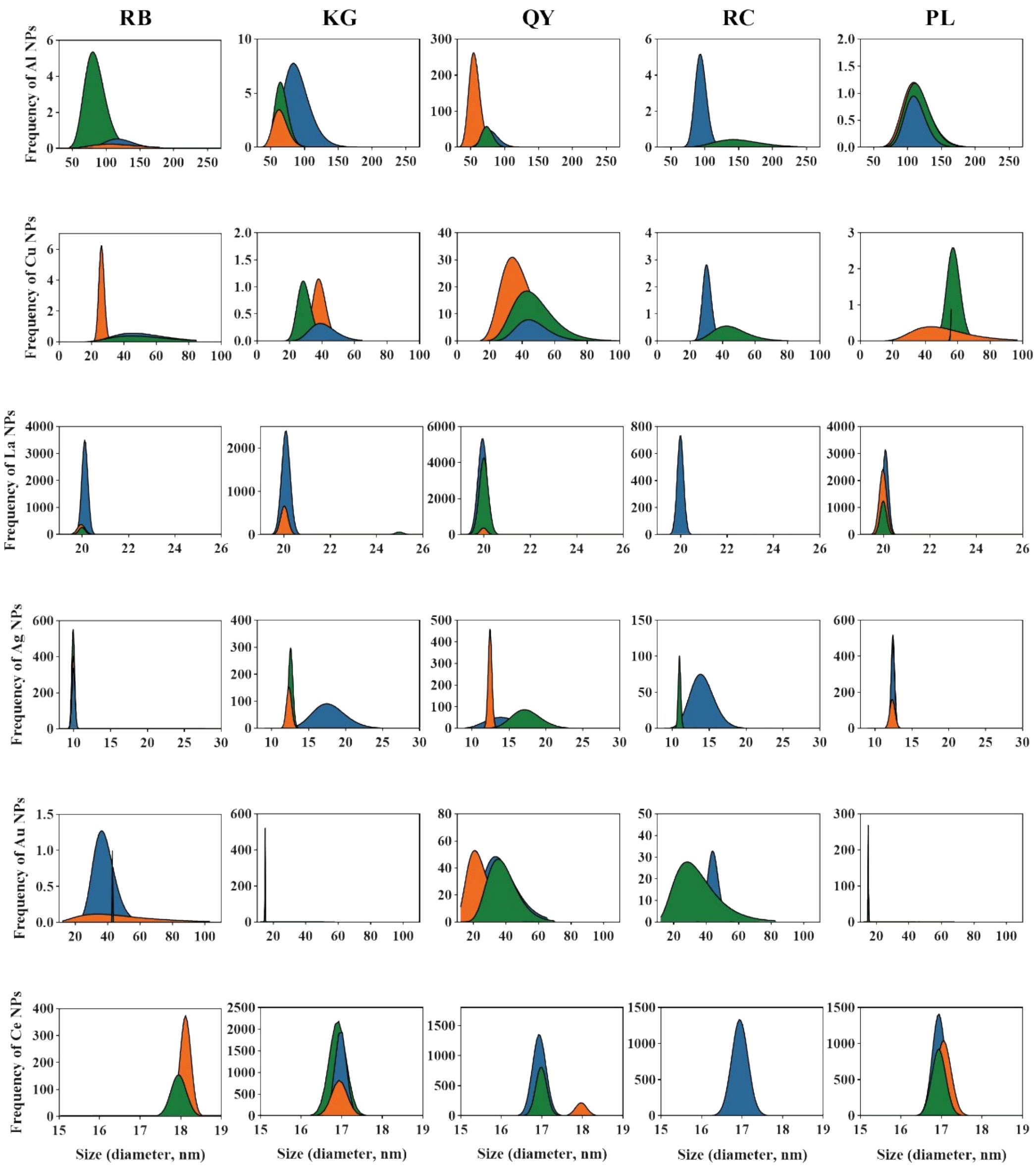

Figure S5. Single-particle size distribution histograms and fitting log-normal distribution curve of Al-, Cu-, La-, Ag-, Au- and Ce-based NPs in glacial runoffs**.** Blue, green, and orange represent upstream, midstream and downstream sampling points. The left axis represents the normalized frequency, ranging from 0 to 100. The right axis represents the fitting log-normal frequency (%), ranging from 0 to 150.

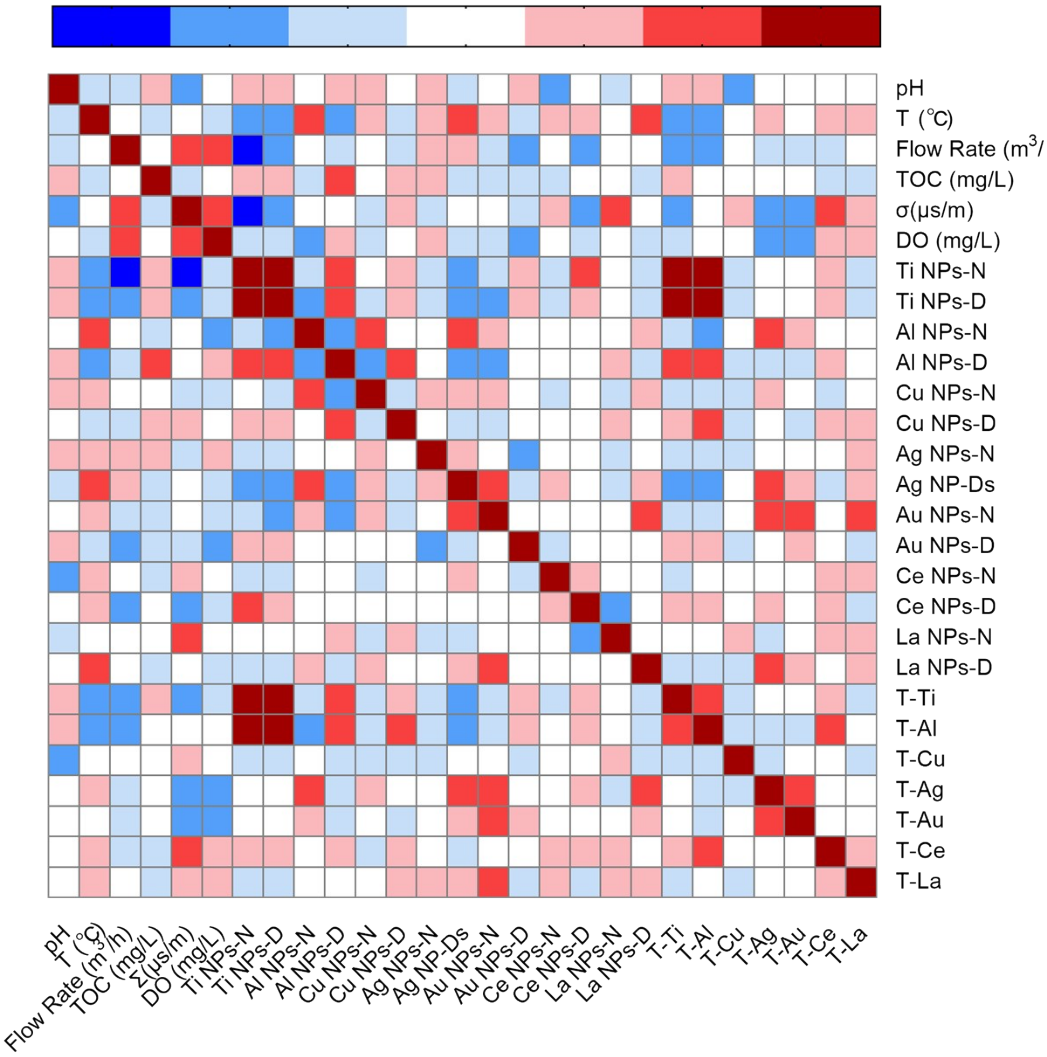

Figure S6. Correlation of 7 MNPs with hydrologic parameters and other MNPs and elements. **D-** represents the mean size of MNPs, **T-** represents the concentration of element. ($p < 0.05$，Kruskal-Wallis test)

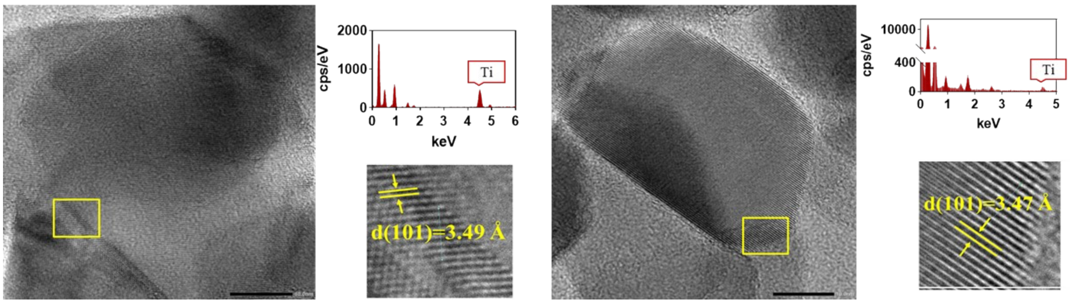

Figure S7. Images of Ti NPs using FETEM and EDXS.

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