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Supplement of

Advancing glacial lake hazard and risk assessment in Bhutan through hydrodynamic flood mapping and exposure analysis

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This supplementary information contains:

Supplementary text: S1

Supplementary figure: Figures S1 to S6

Supplementary table: Tables S1 and S2

S1. Sensitivity analysis

S1.1 Methods

Hydraulic modelling relies on numerous input parameters, some of which are difficult to constrain even with novel field observation data. However, conducting sensitivity analysis for every parameter is highly challenging and deemed unnecessary within the scope of this study, given the scale of GLOF modelling conducted in this study. Here, we therefore focused on Manning's coefficient value and the area of glacial lakes for the sensitivity analysis. n is a well-established sensitive parameter in hydraulic modelling with HEC-RAS 2D, and the area of the lake is essential in our study, as we used it as a proxy for calculating volume and peak discharge using an empirical equation. We examined the interaction impact of n and area of glacial lake variation by modelling 20 scenarios of GLOF, combining four different n (0.04, 0.05, 0.06, 0.07 as suggested by Chow (1959) for cobble beds with large boulders for mountain streams) and five different scenarios of glacial lake area (0.01, 0.05, 0.1, 1, 5 km^2). We assessed how these interactions affect DV, the main hydraulic metric we used for assessing downstream damage from the future potential GLOF.

S1.2 Results

The sensitivity analysis revealed that the mean DV increases proportionately in response to the increase in lake area. For example, when the area of the lake increased by 2 orders of magnitude (0.01 to 5 km), the resulting DV also increased by the same order of magnitude. The variation of Manning's roughness coefficient (n) between 0.04 and 0.07 results in a linear increase in DV ($R^2 > 0.88$) across all area categories (0.01, 0.05, 0.1, 1, and 5 km^2). To evaluate how lake size modulates this sensitivity, we compared the slope (β_1) of all regression equations, which represents the expected change in DV for one unit increase in n. The result indicates that the influence of n on DV becomes progressively more pronounced with increasing lake area. Specifically, when the area was increased from 0.01 to 5 km^2, the value of β_1 increased by one order of magnitude: from 1.23 to 58.7 $m^2\ s^{-1}$. Intermediate values show a consistent upward trend: $\beta_1 = 4.7\ m^2\ s^{-1}$ at 0.05 km^2 and 48.7 $m^2\ s^{-1}$ at 1 km^2, indicating that larger lakes amplify the hydraulic sensitivity to roughness variations (Fig. S6).
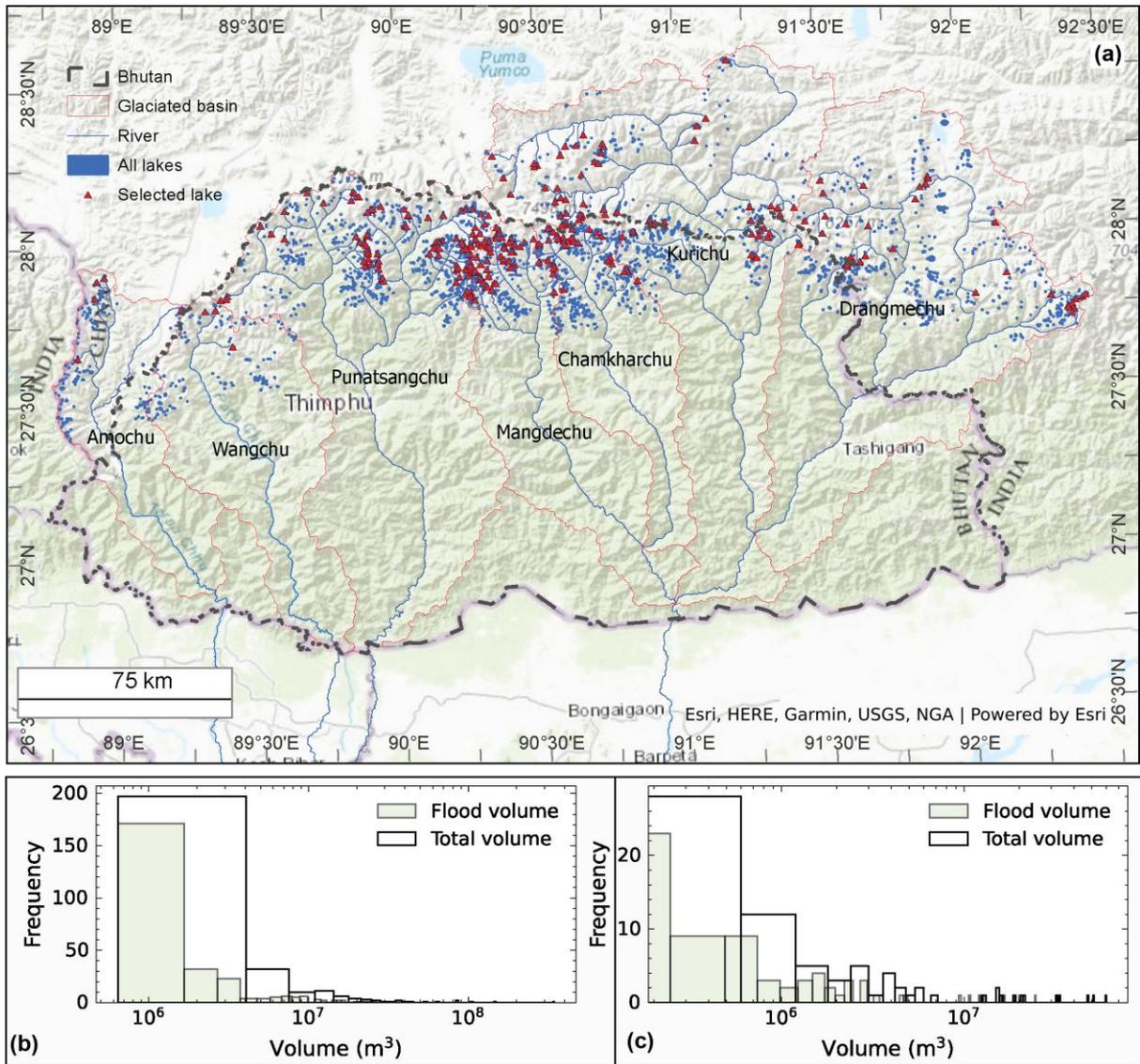
Figure S1. (a) Map shows the distribution of glacial lakes in Bhutan and glacial lakes (with size > 0.05 km² and <1000 m to glacier terminus) selected for GLOF modelling in this study. The histograms depict the distribution of the (b) known total and drainage volumes of historical GLOF in HMA and (c) the total and drainage volumes of lake calculated for this modelling.
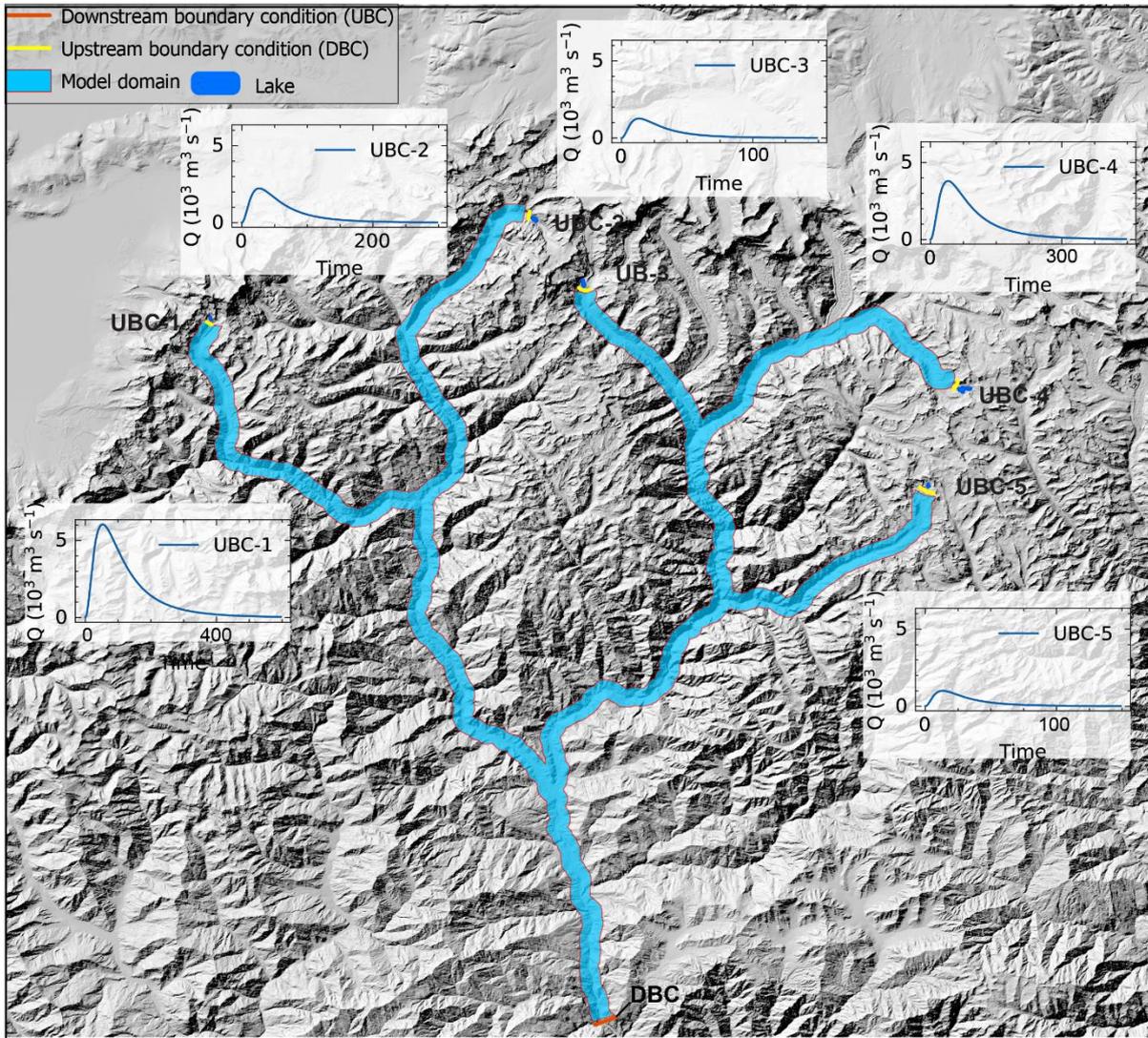
Figure S2. The sample multiple model setup for a basin showing a model domain, upstream boundary conditions, downstream boundary condition, and hydrograph.
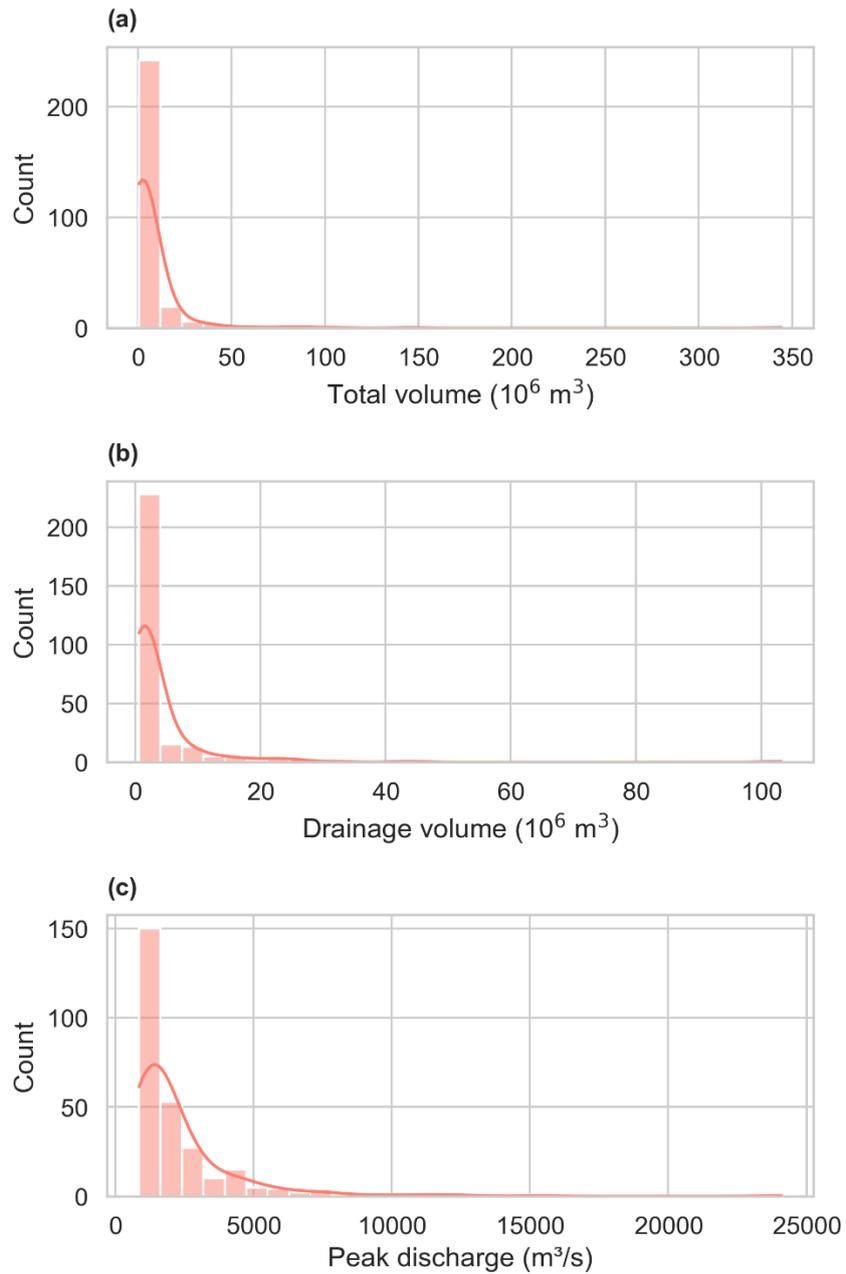
Figure S3. Histogram showing the distribution of (a) total volume, (b) potential drainage volume and (c) peak discharge for the glacial lakes selected for GLOF hazard and risk assessment in Bhutan.
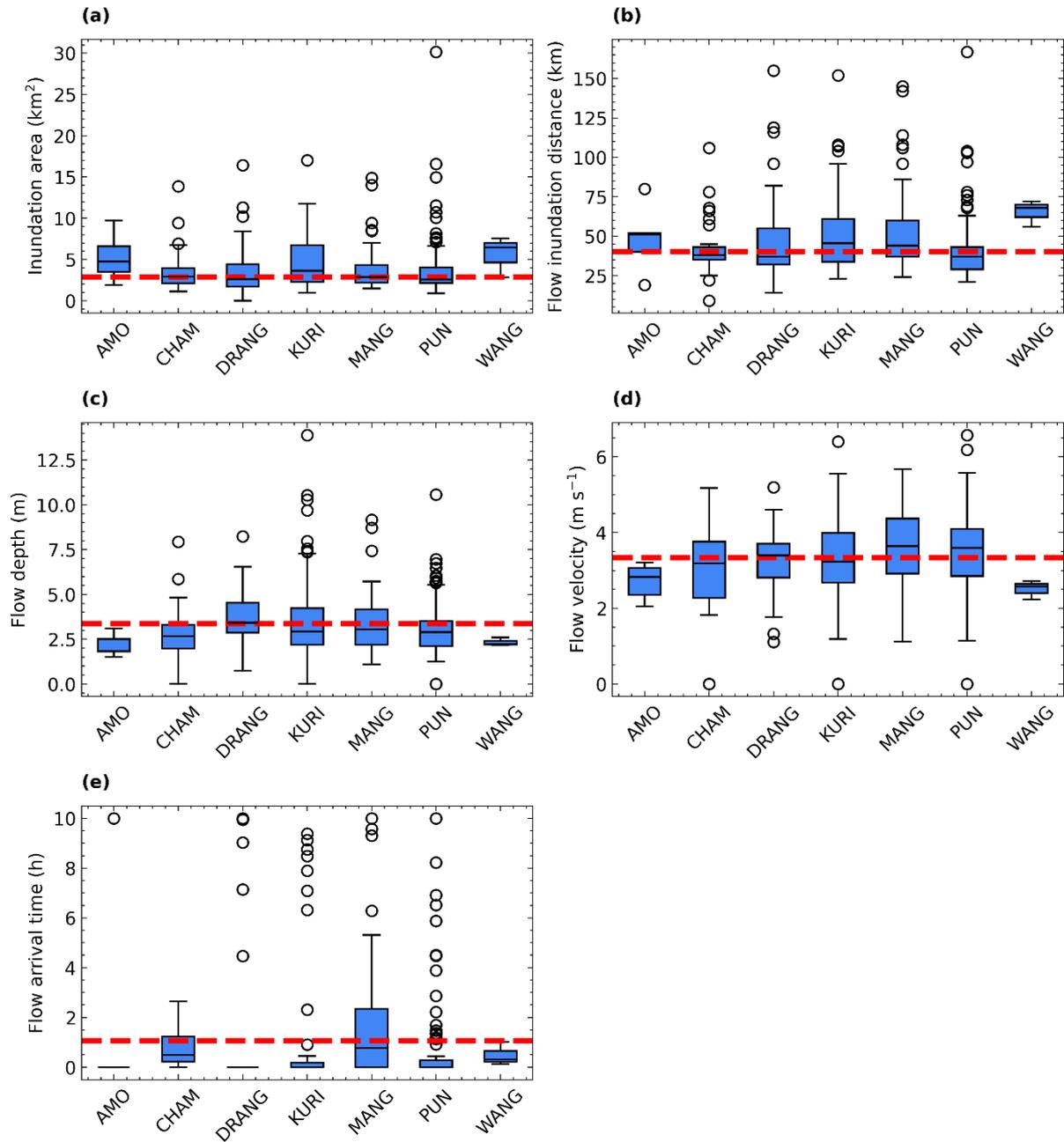
Figure S4. Distribution of (a) inundation area, (b) inundation distance, (c) flow depth, (d) flow velocity, and (e) flow arrival time to the affected building of modelled GLOF for lakes across various basins in Bhutan: including Amochu (AMO), Chamkharchu (CHAM), Drangmechu (DRANG), Kurichu (KURI), Mangdechu (MANG), Punatsangchu (PUN) and Wangchu (WANG). Red dashed line in each panel represents the mean values across all basins.
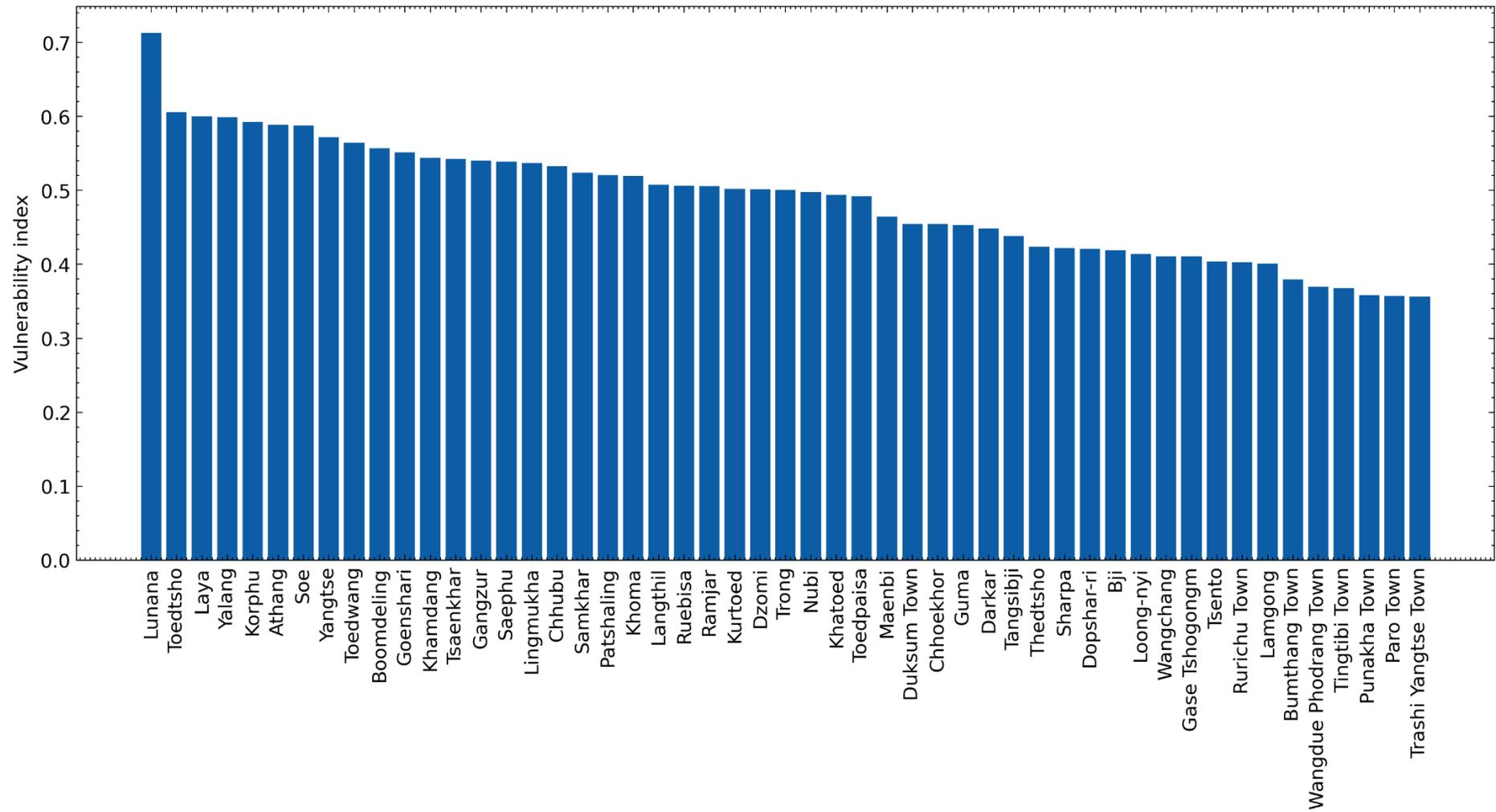
Figure S5. Vulnerability index for each local administrative unit (LGU) computed using Bhutan 2017 population and housing census data for this study.
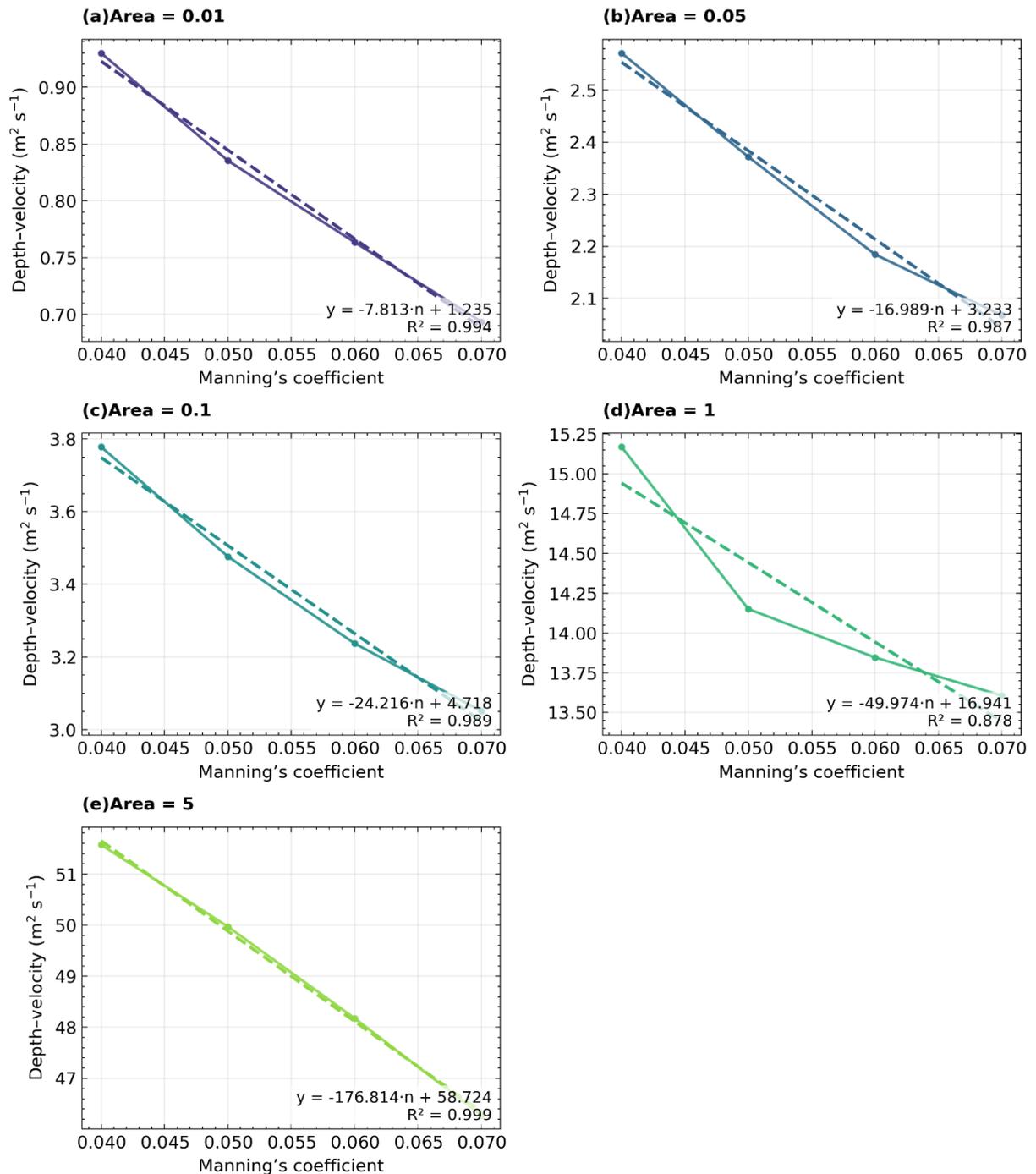
Figure S6. Linear regression fits showing the impact of Manning's roughness coefficient (n) variation on resulting mean depth-velocity across different glacial lake size categories: (a) 0.01, (b) 0.05, (c) 0.1, (d) 1, and (e) 5 km^2. The regression equations and coefficients of determination (R^2) are provided for each lake size.

Table S1. Area, total volume, drainage volume, peak discharge (Qp) and GLOF exposed elements, and danger ranking associated with each glacial lake employed for GLOF modelling in this study. The glacial lakes are arranged in descending order based on their danger index.

| ID	Long	Lat	Elevation m asl)	Area (km²)	Total volume (10^6 m³)	Drainage volume (10^6 m³)	QP (m³ s⁻¹)	Building (count)	Road (km)	Bridge (count)	Farmland (km²)	Danger index	Rank	Danger level
lake130	90.264	28.104	4457.84	4.383	344.07	103.22	24085	1119	71.49	75	4.21	1.0000	1	Very high
lake276	90.710	28.023	4888.33	1.605	83.61	25.08	11380	410	38.16	28	1.01	0.2832	2	High
lake278	89.409	27.687	4787.24	0.181	3.86	2.31	2229	636	38.63	60	2.05	0.2166	3	High
lake262	89.930	27.941	5015.21	0.742	28.20	16.92	6396	339	32.07	44	2.04	0.1860	4	High
lake251	89.350	27.804	4343.42	0.155	3.12	1.87	1992	390	32.15	50	1.62	0.1856	5	High
lake93	90.535	27.939	5049.30	0.603	21.07	12.64	5482	168	32.55	24	0.65	0.1315	6	High
lake18	90.302	28.093	4531.43	1.639	86.11	25.83	11559	184	23.30	22	0.80	0.0799	7	Moderate
lake148	90.374	28.014	5193.29	0.935	39.05	23.43	7601	78	19.06	28	0.53	0.0637	8	Moderate
lake31	90.364	28.037	5217.73	0.851	34.24	20.54	7090	65	18.17	26	0.49	0.0575	9	Moderate
lake186	90.786	28.086	5194.77	2.379	145.53	43.66	15265	48	29.04	30	0.24	0.0471	10	Moderate
lake274	90.540	28.003	4701.28	0.301	7.92	4.75	3262	70	19.72	20	0.21	0.0464	11	Moderate
lake99	89.313	27.800	4380.51	0.056	0.75	0.75	934	82	7.61	24	0.23	0.0449	12	Moderate
lake94	90.555	27.925	4777.80	0.291	7.56	4.54	3184	63	17.58	18	0.19	0.0438	13	Moderate
lake275	90.816	27.897	4717.15	0.451	13.99	8.39	4411	85	14.88	18	0.47	0.0438	14	Moderate
lake128	90.247	28.107	4381.17	1.344	65.14	19.54	9970	83	16.47	20	0.57	0.0394	15	Moderate
lake228	92.437	27.770	5172.98	0.878	35.75	21.45	7254	34	5.41	12	0.34	0.0394	16	Moderate
lake78	92.425	27.763	5097.99	0.203	4.54	2.72	2429	26	3.02	10	0.23	0.0335	17	Moderate
lake44	90.290	27.891	5079.30	1.159	52.85	15.85	8923	26	8.07	20	0.25	0.0328	18	Moderate

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lake71	91.269	27.931	4737.40	0.396	11.67	7.00	4008	51	13.67	26	0.05	0.0317	19	Moderate
lake28	89.896	27.982	5149.94	0.362	10.26	6.15	3742	25	2.84	12	0.12	0.0313	20	Moderate
lake75	91.592	27.894	4742.22	0.053	0.69	0.69	895	46	6.45	0	0.00	0.0298	21	Moderate
lake26	89.884	28.010	5020.81	0.243	5.86	3.51	2781	20	1.56	2	0.00	0.0295	22	Moderate
lake142	89.896	27.974	5135.38	0.248	6.05	3.63	2828	20	1.18	2	0.00	0.0295	23	Moderate
lake22	89.848	28.172	4510.23	0.239	5.74	3.44	2751	25	8.78	16	0.00	0.0276	24	Moderate
lake267	90.418	27.991	5182.51	0.444	13.67	8.20	4358	27	2.85	18	0.21	0.0276	25	Moderate
lake229	92.401	27.756	4965.73	0.142	2.75	1.65	1864	21	2.47	8	0.20	0.0258	26	Moderate
lake167	90.355	28.047	5266.11	0.502	16.28	9.77	4781	21	12.43	14	0.20	0.0236	27	Moderate
lake27	89.892	27.988	5132.59	0.133	2.50	1.50	1769	20	1.11	2	0.00	0.0214	28	Moderate
lake82	90.625	28.035	5178.27	0.320	8.62	5.17	3413	29	13.31	22	0.06	0.0180	29	Low
lake161	90.303	27.873	5047.95	0.429	13.04	7.82	4250	19	6.00	10	0.18	0.0158	30	Low
lake201	91.287	27.996	4513.99	0.252	6.16	3.70	2856	26	7.27	12	0.02	0.0151	31	Low
lake81	90.546	28.038	5004.31	0.182	3.90	2.34	2242	12	12.57	12	0.00	0.0144	32	Low
lake95	90.559	27.916	4932.11	0.110	1.91	1.15	1535	13	9.08	6	0.00	0.0144	33	Low
lake234	90.537	28.041	5000.80	0.189	4.10	2.46	2302	14	12.91	12	0.00	0.0144	34	Low
lake238	90.572	28.006	5157.16	0.150	2.96	1.78	1937	12	11.42	10	0.00	0.0136	35	Low
lake134	89.841	28.144	5118.27	0.131	2.44	1.47	1750	25	5.23	12	0.00	0.0129	36	Low
lake23	89.853	28.167	4549.27	0.106	1.82	1.09	1499	19	6.52	12	0.00	0.0125	37	Low
lake170	91.079	28.351	4800.95	0.993	42.55	25.53	7955	12	10.50	12	0.14	0.0122	38	Low

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lake245	90.553	27.913	4981.97	0.064	0.90	0.90	1030	9	7.84	6	0.00	0.0118	39	Low
lake90	90.505	27.988	5199.22	0.193	4.24	2.55	2344	9	10.85	12	0.00	0.0110	40	Low
lake242	90.599	27.984	5030.51	0.079	1.20	1.20	1202	14	13.95	14	0.00	0.0110	41	Low
lake34	90.328	28.005	5369.63	0.363	10.30	6.18	3750	13	12.90	6	0.04	0.0099	42	Low
lake129	90.231	28.103	4353.40	0.472	14.94	8.96	4568	12	7.50	10	0.00	0.0096	43	Low
lake144	89.884	27.937	4890.92	0.091	1.47	1.47	1335	20	1.00	2	0.00	0.0092	44	Low
lake11	89.930	27.973	5068.03	0.661	23.98	14.39	5870	24	3.39	10	0.32	0.0088	45	Low
lake21	89.685	28.172	4780.37	0.102	1.74	1.04	1460	16	1.95	14	0.00	0.0088	46	Low
lake37	90.412	27.968	5213.42	0.245	5.93	3.56	2800	17	1.27	10	0.04	0.0088	47	Low
lake57	90.724	28.242	4662.12	0.911	37.69	22.61	7460	9	7.93	10	0.11	0.0088	48	Low
lake135	89.742	28.139	4858.81	0.118	2.13	1.28	1626	19	2.28	10	0.00	0.0088	49	Low
lake138	89.855	28.030	4761.94	0.083	1.30	1.30	1250	20	0.99	2	0.00	0.0085	50	Low
lake136	89.602	28.115	4162.88	0.072	1.06	1.06	1123	16	2.13	10	0.00	0.0074	51	Low
lake137	89.600	28.027	4988.49	0.127	2.35	1.41	1715	15	2.56	8	0.00	0.0070	52	Low
lake139	89.868	28.012	4906.88	0.083	1.30	1.30	1250	20	0.98	2	0.00	0.0070	53	Low
lake140	89.885	28.008	5021.95	0.061	0.84	0.84	993	14	0.84	2	0.00	0.0070	54	Low
lake141	89.890	28.001	5086.74	0.087	1.37	1.37	1290	20	0.98	2	0.00	0.0070	55	Low
lake235	90.558	28.027	5121.19	0.084	1.32	1.32	1262	7	8.85	8	0.00	0.0070	56	Low
lake266	89.881	27.952	4955.72	0.069	1.00	1.00	1088	15	0.98	2	0.00	0.0070	57	Low
lake270	90.437	27.984	5108.12	0.273	6.90	4.14	3034	17	1.23	10	0.04	0.0070	58	Low

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lake10	90.233	27.978	5085.79	0.688	25.35	15.21	6046	17	3.86	10	0.32	0.0066	59	Low
lake54	90.736	28.274	4504.37	1.890	105.22	31.57	12854	7	7.07	8	0.11	0.0066	60	Low
lake91	90.593	27.983	5035.38	0.128	2.37	1.42	1723	9	8.82	8	0.00	0.0066	61	Low
lake246	90.812	27.907	4804.80	0.360	10.20	6.12	3731	16	6.71	12	0.01	0.0066	62	Low
lake133	89.868	28.156	5058.72	0.054	0.70	0.70	901	5	4.91	10	0.00	0.0052	63	Low
lake160	90.551	27.895	4974.02	0.238	5.68	3.41	2735	11	0.68	8	0.01	0.0052	64	Low
lake241	90.505	27.993	5201.94	0.090	1.44	1.44	1321	7	7.41	8	0.00	0.0048	65	Low
lake84	90.571	28.018	5191.71	0.082	1.26	1.26	1231	7	5.51	8	0.00	0.0041	66	Low
lake92	90.756	27.942	5025.36	0.177	3.76	2.25	2198	5	9.48	14	0.00	0.0041	67	Low
lake36	90.331	27.970	5322.69	0.249	6.06	3.64	2831	9	10.21	6	0.01	0.0037	68	Low
lake87	90.593	27.997	5114.92	0.148	2.90	1.74	1917	6	5.34	8	0.00	0.0037	69	Low
lake240	90.607	27.996	5238.18	0.057	0.76	0.76	940	6	5.16	8	0.00	0.0037	70	Low
lake51	90.272	27.819	4905.20	0.216	4.95	2.97	2544	8	3.88	4	0.01	0.0033	71	Low
lake83	90.684	28.034	4797.11	0.059	0.80	0.80	971	5	5.98	10	0.00	0.0033	72	Low
lake86	90.628	28.006	5061.56	0.090	1.45	1.45	1326	3	7.83	12	0.00	0.0033	73	Low
lake88	90.624	27.995	5094.78	0.070	1.02	1.02	1101	3	7.37	10	0.00	0.0033	74	Low
lake89	90.644	27.992	4854.31	0.083	1.29	1.29	1248	3	7.83	12	0.00	0.0033	75	Low
lake237	90.620	28.007	5145.91	0.070	1.02	1.02	1103	2	6.65	10	0.00	0.0033	76	Low
lake156	90.397	27.940	5207.01	0.197	4.37	2.62	2380	7	0.36	6	0.01	0.0029	77	Low
lake202	91.325	28.002	4792.03	0.059	0.79	0.79	962	5	0.02	0	0.00	0.0029	78	Low

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lake273	90.903	28.059	4764.34	0.545	18.27	10.96	5082	6	4.43	6	0.09	0.0029	79	Low
lake195	91.292	28.012	4624.33	0.116	2.06	1.24	1598	8	0.33	0	0.00	0.0026	80	Low
lake200	90.850	27.866	4585.56	0.096	1.57	1.57	1386	3	0.47	2	0.00	0.0026	81	Low
lake236	90.592	28.010	5146.84	0.053	0.69	0.69	895	6	4.73	6	0.00	0.0022	82	Low
lake239	90.801	28.006	5078.83	0.064	0.89	0.89	1023	2	6.09	10	0.00	0.0022	83	Low
lake243	90.748	27.931	4980.44	0.072	1.06	1.06	1125	2	6.10	10	0.00	0.0022	84	Low
lake42	90.276	27.907	5158.45	0.233	5.52	3.31	2696	2	4.97	2	0.01	0.0018	85	Low
lake158	90.408	27.919	5140.74	0.180	3.85	2.31	2227	7	0.36	6	0.01	0.0018	86	Low
lake164	90.554	27.837	4796.94	0.115	2.05	1.23	1595	0	0.19	2	0.01	0.0018	87	Low
lake69	91.307	28.018	4963.15	0.091	1.47	1.47	1335	3	0.00	0	0.00	0.0015	88	Low
lake197	91.317	27.990	4760.71	0.061	0.84	0.84	996	7	0.00	0	0.00	0.0015	89	Low
lake244	90.763	27.921	4952.03	0.081	1.25	1.25	1226	3	1.86	4	0.00	0.0015	90	Low
lake254	90.113	28.084	4133.79	0.100	1.69	1.01	1437	3	2.18	4	0.00	0.0015	91	Low
lake62	91.257	28.088	4630.52	0.608	21.34	12.80	5518	3	1.89	6	0.09	0.0011	92	Low
lake66	90.953	28.049	4642.29	0.388	11.34	6.80	3947	3	1.89	6	0.08	0.0011	93	Low
lake105	90.211	28.016	5132.17	0.570	19.45	11.67	5253	1	4.27	12	0.14	0.0011	94	Low
lake152	90.381	27.981	5237.29	0.217	5.01	3.01	2560	2	8.43	2	0.01	0.0011	95	Low
lake162	90.333	27.849	5037.33	0.138	2.63	1.58	1820	2	0.21	2	0.01	0.0011	96	Low
lake198	91.426	27.963	4855.93	0.139	2.66	1.60	1831	3	0.56	0	0.00	0.0011	97	Low
lake199	91.257	27.936	4848.75	0.073	1.07	1.07	1129	2	0.00	0	0.00	0.0011	98	Low

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lake205	91.276	27.926	4853.90	0.071	1.03	1.03	1109	2	0.00	0	0.00	0.0011	99	Low
lake7	90.289	27.996	5332.95	0.488	15.63	9.38	4678	2	10.68	6	0.00	0.0007	100	Low
lake70	91.430	27.967	4824.95	0.074	1.09	1.09	1142	2	0.02	0	0.00	0.0007	101	Low
lake85	90.728	28.012	5157.87	0.052	0.67	0.67	884	2	2.80	4	0.00	0.0007	102	Low
lake231	92.393	27.725	5234.39	0.054	0.70	0.70	904	1	0.26	2	0.00	0.0007	103	Low
lake35	90.380	27.987	5245.93	0.156	3.14	1.89	2000	1	7.24	2	0.01	0.0004	104	Low
lake104	90.270	28.029	5208.17	0.256	6.31	3.78	2892	1	6.09	6	0.00	0.0004	105	Low
lake116	89.906	27.941	5023.62	0.142	2.75	1.65	1864	1	4.42	6	0.02	0.0004	106	Low
lake147	90.353	28.014	5288.47	0.179	3.80	2.28	2213	1	7.37	2	0.01	0.0004	107	Low
lake155	90.378	27.946	5266.29	0.155	3.12	1.87	1991	1	5.67	2	0.01	0.0004	108	Low
lake1	89.945	28.124	4755.76	0.071	1.04	1.04	1110	0	3.99	4	0.00	0	109	Low
lake2	90.042	28.092	5041.48	0.094	1.54	1.54	1371	0	0.08	2	0.00	0	109	Low
lake3	89.893	28.029	5037.16	0.111	1.94	1.17	1550	0	2.34	6	0.00	0	109	Low
lake4	90.161	28.010	5042.49	0.082	1.28	1.28	1242	0	0.00	0	0.00	0	109	Low
lake5	90.277	28.008	5287.38	0.143	2.77	1.66	1870	0	5.96	4	0.00	0	109	Low
lake6	90.139	28.002	5065.13	0.166	3.41	2.05	2089	0	0.00	0	0.00	0	109	Low
lake8	90.261	27.996	5133.97	0.214	4.89	2.93	2527	0	6.54	6	0.00	0	109	Low
lake9	90.300	27.992	5346.14	0.161	3.28	1.97	2045	0	5.93	4	0.00	0	109	Low
lake12	89.933	27.924	4849.36	0.073	1.07	1.07	1128	0	4.26	4	0.00	0	109	Low
lake13	90.244	27.922	5117.31	0.060	0.82	0.82	980	0	0.29	0	0.00	0	109	Low

ID	Long	Lat	Elevation m asl)	Area (km^2)	Total volume (10^6 m^3)	Drainage volume (10^6 m^3)	QP (m^3 s^{-1})	Building (count)	Road (km)	Bridge (count)	Farmland (km^2)	Danger index	Rank	Danger level
lake14	90.209	27.917	4902.46	0.083	1.29	1.29	1246	0	0.00	0	0.00	0	109	Low
lake15	89.943	27.893	4854.45	0.098	1.62	1.62	1409	0	0.00	0	0.00	0	109	Low
lake16	90.219	27.893	4980.17	0.176	3.71	2.23	2183	0	0.00	0	0.00	0	109	Low
lake17	89.949	27.886	4564.59	0.061	0.83	0.83	986	0	0.00	0	0.00	0	109	Low
lake19	90.327	28.086	4698.54	0.055	0.72	0.72	919	0	2.04	8	0.00	0	109	Low
lake20	90.313	28.059	5104.05	0.085	1.33	1.33	1270	0	3.18	8	0.00	0	109	Low
lake24	89.516	28.070	4770.28	0.075	1.11	1.11	1152	0	0.56	4	0.00	0	109	Low
lake25	89.554	28.044	4881.61	0.051	0.65	0.65	867	0	4.46	8	0.00	0	109	Low
lake29	89.393	27.849	4211.70	0.084	1.32	1.32	1263	0	0.35	4	0.00	0	109	Low
lake30	89.389	27.839	4328.35	0.178	3.77	2.26	2202	0	0.42	4	0.00	0	109	Low
lake32	90.407	28.012	5286.28	0.083	1.30	1.30	1252	0	0.06	0	0.00	0	109	Low
lake33	90.485	28.008	5017.74	0.072	1.07	1.07	1127	0	0.06	0	0.00	0	109	Low
lake38	90.366	27.957	5261.97	0.057	0.75	0.75	937	0	4.29	0	0.00	0	109	Low
lake39	90.377	27.941	5215.20	0.089	1.42	1.42	1313	0	4.81	0	0.00	0	109	Low
lake40	90.503	27.933	5057.38	0.086	1.35	1.35	1279	0	0.06	0	0.00	0	109	Low
lake41	90.414	27.928	5016.17	0.068	0.98	0.98	1080	0	0.06	0	0.00	0	109	Low
lake43	90.322	27.893	5109.13	0.080	1.22	1.22	1212	0	2.67	0	0.00	0	109	Low
lake45	90.293	27.883	5112.76	0.094	1.55	1.55	1375	0	2.27	0	0.00	0	109	Low
lake46	90.298	27.884	5123.49	0.158	3.19	1.92	2016	0	2.54	2	0.00	0	109	Low
lake47	90.342	27.870	5081.63	0.075	1.11	1.11	1154	0	2.45	0	0.00	0	109	Low

ID	Long	Lat	Elevation m asl)	Area (km^2)	Total volume (10^6 m^3)	Drainage volume (10^6 m^3)	QP (m^3 s^{-1})	Building (count)	Road (km)	Bridge (count)	Farmland (km^2)	Danger index	Rank	Danger level
lake48	90.349	27.869	5068.53	0.079	1.20	1.20	1200	0	2.61	0	0.00	0	109	Low
lake49	90.311	27.859	4965.92	0.111	1.94	1.16	1548	0	2.39	0	0.00	0	109	Low
lake50	90.318	27.858	5071.02	0.062	0.85	0.85	1003	0	2.07	0	0.00	0	109	Low
lake52	90.674	28.334	4636.53	0.116	2.07	1.24	1604	0	0.00	0	0.00	0	109	Low
lake53	90.745	28.296	4727.84	0.127	2.35	1.41	1715	0	1.43	0	0.00	0	109	Low
lake55	90.712	28.247	4685.09	0.195	4.30	2.58	2361	0	0.00	0	0.00	0	109	Low
lake56	90.506	28.241	5469.52	0.219	5.06	3.04	2575	0	0.00	0	0.00	0	109	Low
lake58	90.409	28.152	4843.89	0.088	1.39	1.39	1299	0	0.00	0	0.00	0	109	Low
lake59	90.667	28.115	5158.24	0.067	0.96	0.96	1065	0	0.20	0	0.00	0	109	Low
lake60	90.738	28.096	5021.60	0.726	27.39	16.43	6298	0	1.14	0	0.00	0	109	Low
lake61	90.584	28.078	5311.31	0.111	1.95	1.17	1554	0	3.14	0	0.00	0	109	Low
lake63	90.656	28.072	5027.28	0.435	13.31	7.99	4297	0	6.93	0	0.00	0	109	Low
lake64	90.601	28.059	4889.58	0.440	13.50	8.10	4329	0	6.28	0	0.00	0	109	Low
lake65	90.597	28.049	5010.45	0.343	9.53	5.72	3600	0	4.58	0	0.00	0	109	Low
lake67	91.294	28.043	4777.73	0.137	2.61	1.57	1812	0	2.73	0	0.00	0	109	Low
lake68	90.843	28.019	4979.87	0.192	4.22	2.53	2338	0	0.06	2	0.04	0	109	Low
lake72	90.907	28.041	4911.79	0.118	2.12	1.27	1623	0	0.92	0	0.00	0	109	Low
lake73	90.346	28.274	5610.76	0.052	0.67	0.67	884	0	0.00	0	0.00	0	109	Low
lake74	91.451	28.037	4742.27	0.564	19.17	11.50	5214	0	0.00	0	0.00	0	109	Low
lake76	91.596	27.887	4604.65	0.175	3.68	2.21	2173	0	0.47	16	0.71	0	109	Low

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lake77	92.315	27.774	4876.40	0.131	2.44	1.47	1750	0	0.00	0	0.00	0	109	Low
lake79	92.375	27.738	5044.48	0.076	1.13	1.13	1163	0	0.00	0	0.00	0	109	Low
lake80	92.374	27.733	5083.44	0.075	1.13	1.13	1162	0	0.00	0	0.00	0	109	Low
lake96	88.922	27.847	4629.59	0.063	0.87	0.87	1011	0	0.00	0	0.00	0	109	Low
lake97	88.858	27.654	4746.86	0.115	2.04	1.22	1589	0	0.00	0	0.00	0	109	Low
lake98	90.319	27.943	5230.06	0.052	0.67	0.67	884	0	2.86	0	0.00	0	109	Low
lake100	90.028	28.113	4689.50	0.369	10.56	6.34	3801	0	0.36	6	0.00	0	109	Low
lake101	90.043	28.096	5116.29	0.068	0.98	0.98	1081	0	0.06	0	0.00	0	109	Low
lake102	89.894	28.036	5188.97	0.061	0.84	0.84	994	0	1.98	6	0.00	0	109	Low
lake103	90.295	28.030	5315.89	0.087	1.37	1.37	1287	0	0.00	8	0.00	0	109	Low
lake106	90.280	28.013	5291.12	0.175	3.70	2.22	2179	0	6.48	6	0.00	0	109	Low
lake107	90.149	28.009	5027.32	0.071	1.04	1.04	1115	0	0.00	0	0.00	0	109	Low
lake108	90.139	28.007	5056.02	0.095	1.57	1.57	1383	0	0.00	0	0.00	0	109	Low
lake109	90.231	28.005	5078.31	0.061	0.83	0.83	987	0	0.97	0	0.00	0	109	Low
lake110	90.234	27.997	4986.31	0.123	2.24	1.34	1670	0	1.18	0	0.00	0	109	Low
lake111	90.263	27.988	5160.14	0.103	1.75	1.05	1465	0	5.31	4	0.00	0	109	Low
lake112	90.245	27.983	5101.78	0.189	4.11	2.46	2304	0	0.12	0	0.00	0	109	Low
lake113	90.114	27.969	5003.91	0.113	2.00	1.20	1574	0	0.00	0	0.00	0	109	Low
lake114	90.260	27.964	5221.01	0.470	14.83	8.90	4550	0	0.30	2	0.00	0	109	Low
lake115	89.933	27.950	5048.71	0.074	1.09	1.09	1142	0	3.80	2	0.00	0	109	Low

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lake117	90.257	27.943	5194.89	0.070	1.01	1.01	1096	0	0.63	0	0.00	0	109	Low
lake118	90.209	27.932	4993.61	0.124	2.27	1.36	1681	0	0.00	0	0.00	0	109	Low
lake119	90.216	27.922	5190.54	0.075	1.12	1.12	1159	0	0.00	0	0.00	0	109	Low
lake120	90.263	27.920	5147.12	0.240	5.75	3.45	2754	0	0.50	0	0.00	0	109	Low
lake121	90.244	27.915	5169.16	0.226	5.30	3.18	2637	0	0.43	0	0.00	0	109	Low
lake122	89.946	27.896	4865.74	0.085	1.34	1.34	1274	0	0.00	0	0.00	0	109	Low
lake123	90.252	27.897	5154.51	0.093	1.52	1.52	1363	0	0.00	0	0.00	0	109	Low
lake124	90.207	27.876	4910.99	0.409	12.21	7.33	4105	0	0.00	0	0.00	0	109	Low
lake125	90.259	27.843	5023.90	0.086	1.35	1.35	1276	0	0.00	0	0.00	0	109	Low
lake126	90.253	27.841	4997.01	0.098	1.63	1.63	1412	0	0.00	0	0.00	0	109	Low
lake127	90.237	27.837	4772.21	0.079	1.20	1.20	1201	0	0.00	0	0.00	0	109	Low
lake131	90.280	28.050	5059.53	0.053	0.70	0.70	899	0	2.19	8	0.00	0	109	Low
lake132	90.167	28.091	4221.34	0.055	0.72	0.72	917	0	0.85	2	0.00	0	109	Low
lake143	89.897	27.958	5092.52	0.102	1.74	1.04	1460	0	0.00	0	0.00	0	109	Low
lake145	89.369	27.836	4423.57	0.051	0.64	0.64	863	0	0.27	2	0.00	0	109	Low
lake146	90.357	28.025	5331.06	0.063	0.88	0.88	1017	0	3.14	0	0.00	0	109	Low
lake149	90.311	28.003	5455.31	0.112	1.97	1.18	1559	0	7.32	0	0.00	0	109	Low
lake150	90.452	27.998	5003.06	0.092	1.49	1.49	1345	0	0.06	0	0.00	0	109	Low
lake151	90.398	27.997	5344.28	0.055	0.72	0.72	913	0	0.04	0	0.00	0	109	Low
lake153	90.405	27.967	5267.02	0.080	1.23	1.23	1216	0	0.07	0	0.00	0	109	Low

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lake154	90.282	27.956	5224.93	0.051	0.66	0.66	872	0	1.07	0	0.00	0	109	Low
lake157	90.295	27.932	5191.36	0.098	1.64	1.64	1416	0	2.68	0	0.00	0	109	Low
lake159	90.268	27.909	5180.90	0.090	1.45	1.45	1326	0	4.26	0	0.00	0	109	Low
lake163	90.255	27.831	5062.18	0.055	0.72	0.72	913	0	2.11	0	0.00	0	109	Low
lake165	90.317	27.914	5195.17	0.096	1.58	1.58	1389	0	3.65	0	0.00	0	109	Low
lake166	90.400	27.918	5211.81	0.081	1.24	1.24	1221	0	0.07	0	0.00	0	109	Low
lake168	90.275	27.913	5182.61	0.069	1.00	1.00	1091	0	3.53	0	0.00	0	109	Low
lake169	91.191	28.557	5342.65	0.101	1.70	1.02	1443	0	0.00	0	0.00	0	109	Low
lake171	90.741	28.304	4772.27	0.108	1.88	1.13	1524	0	0.00	0	0.00	0	109	Low
lake172	90.608	28.300	5358.88	0.168	3.50	2.10	2116	0	0.00	0	0.00	0	109	Low
lake173	91.069	28.305	4729.41	0.186	4.02	2.41	2277	0	0.00	0	0.00	0	109	Low
lake174	90.647	28.301	5472.55	0.317	8.52	5.11	3393	0	0.00	0	0.00	0	109	Low
lake175	90.589	28.272	5424.23	0.476	15.12	9.07	4598	0	0.00	0	0.00	0	109	Low
lake176	90.496	28.238	5620.52	0.228	5.36	3.22	2653	0	0.00	0	0.00	0	109	Low
lake177	90.663	28.207	5074.60	0.084	1.32	1.32	1264	0	0.00	0	0.00	0	109	Low
lake178	90.576	28.167	5402.23	0.057	0.76	0.76	939	0	0.00	0	0.00	0	109	Low
lake179	90.587	28.136	5359.05	0.057	0.77	0.77	947	0	0.00	0	0.00	0	109	Low
lake180	90.605	28.129	5198.36	0.102	1.72	1.03	1451	0	0.00	0	0.00	0	109	Low
lake181	90.605	28.086	5203.61	0.350	9.79	5.88	3652	0	4.62	0	0.00	0	109	Low
lake182	90.661	28.078	5085.37	0.132	2.48	1.49	1762	0	4.20	0	0.00	0	109	Low

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lake183	91.334	28.088	5146.03	0.057	0.76	0.76	944	0	0.00	0	0.00	0	109	Low
lake184	90.743	28.078	5157.81	0.240	5.75	3.45	2754	0	0.00	0	0.00	0	109	Low
lake185	91.357	28.082	4870.25	0.063	0.88	0.88	1017	0	0.03	0	0.00	0	109	Low
lake187	91.415	28.081	5376.28	0.066	0.93	0.93	1049	0	0.00	0	0.00	0	109	Low
lake188	90.648	28.065	5115.18	0.248	6.02	3.61	2821	0	4.90	0	0.00	0	109	Low
lake189	91.364	28.062	4629.15	0.081	1.24	1.24	1223	0	0.42	0	0.00	0	109	Low
lake190	90.898	28.053	4769.02	0.075	1.12	1.12	1158	0	0.91	0	0.00	0	109	Low
lake191	90.587	28.048	5153.17	0.090	1.46	1.46	1330	0	3.44	0	0.00	0	109	Low
lake192	90.919	28.047	4928.76	0.178	3.78	2.27	2203	0	1.02	0	0.00	0	109	Low
lake193	91.261	28.045	4582.99	0.122	2.22	1.33	1663	0	1.86	0	0.00	0	109	Low
lake194	90.840	28.022	4992.07	0.220	5.08	3.05	2580	0	0.09	2	0.04	0	109	Low
lake196	91.262	28.001	4475.73	0.185	3.98	2.39	2265	0	1.19	0	0.00	0	109	Low
lake203	90.566	28.123	5183.26	0.670	24.45	14.67	5931	0	1.13	0	0.00	0	109	Low
lake204	90.496	28.248	5654.92	0.056	0.74	0.74	927	0	0.00	0	0.00	0	109	Low
lake206	90.385	28.204	5439.54	0.424	12.82	7.69	4212	0	0.00	0	0.00	0	109	Low
lake207	91.112	28.374	5308.48	0.051	0.64	0.64	863	0	0.00	0	0.00	0	109	Low
lake208	91.510	28.164	5228.11	0.131	2.47	1.48	1759	0	0.00	0	0.00	0	109	Low
lake209	91.893	28.165	5209.90	0.054	0.71	0.71	909	0	0.00	0	0.00	0	109	Low
lake210	91.895	28.159	5210.67	0.052	0.66	0.66	876	0	0.00	0	0.00	0	109	Low
lake211	91.664	28.143	5148.10	0.212	4.83	2.90	2511	0	0.00	0	0.00	0	109	Low

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lake212	91.887	28.141	5247.76	0.103	1.75	1.05	1468	0	0.00	0	0.00	0	109	Low
lake213	91.864	28.132	5410.38	0.082	1.28	1.28	1241	0	0.00	0	0.00	0	109	Low
lake214	91.520	28.124	5179.74	0.056	0.75	0.75	935	0	0.00	0	0.00	0	109	Low
lake215	91.847	28.094	5170.85	0.067	0.95	0.95	1062	0	0.00	0	0.00	0	109	Low
lake216	91.597	28.023	4830.26	0.391	11.45	6.87	3967	0	0.00	0	0.00	0	109	Low
lake217	91.676	28.014	4421.65	0.133	2.51	1.51	1777	0	0.00	0	0.00	0	109	Low
lake218	92.128	28.010	5031.89	0.071	1.04	1.04	1113	0	0.00	0	0.00	0	109	Low
lake219	91.511	27.996	5335.54	0.180	3.83	2.30	2220	0	0.00	0	0.00	0	109	Low
lake220	91.760	27.939	4510.01	0.073	1.07	1.07	1129	0	0.00	0	0.00	0	109	Low
lake221	91.662	27.919	4721.89	0.056	0.74	0.74	929	0	2.32	0	0.00	0	109	Low
lake222	91.610	27.918	4636.99	0.104	1.77	1.06	1475	0	0.00	0	0.00	0	109	Low
lake223	91.642	27.901	4990.08	0.056	0.74	0.74	927	0	0.00	0	0.00	0	109	Low
lake224	91.619	27.901	4938.35	0.143	2.77	1.66	1871	0	0.00	0	0.00	0	109	Low
lake225	91.596	27.896	4755.40	0.055	0.72	0.72	917	0	0.17	0	0.00	0	109	Low
lake226	92.161	27.851	4824.62	0.159	3.22	1.93	2024	0	0.00	0	0.00	0	109	Low
lake227	92.048	27.789	4953.98	0.116	2.07	1.24	1604	0	0.00	0	0.00	0	109	Low
lake230	92.388	27.744	5091.91	0.091	1.46	1.46	1334	0	0.00	0	0.00	0	109	Low
lake232	92.386	27.715	5104.45	0.129	2.41	1.44	1736	0	0.00	0	0.00	0	109	Low
lake233	91.525	28.050	5091.36	0.108	1.88	1.13	1522	0	0.00	0	0.00	0	109	Low
lake247	90.587	27.845	5132.52	0.098	1.63	1.63	1413	0	0.96	2	0.00	0	109	Low

ID	Long	Lat	Elevation m asl)	Area (km²)	Total volume (10⁶ m³)	Drainage volume (10⁶ m³)	QP (m³ s⁻¹)	Building (count)	Road (km)	Bridge (count)	Farmland (km²)	Danger index	Rank	Danger level
lake248	88.956	27.913	4812.30	0.067	0.96	0.96	1064	0	0.00	0	0.00	0	109	Low
lake249	89.229	27.809	5137.19	0.477	15.16	9.09	4603	0	0.00	0	0.00	0	109	Low
lake250	88.930	27.900	5104.26	0.175	3.68	2.21	2175	0	1.34	0	0.00	0	109	Low
lake252	89.909	28.114	4364.76	0.457	14.28	8.57	4459	0	7.59	8	0.00	0	109	Low
lake253	89.899	28.106	4268.83	0.253	6.22	3.73	2870	0	6.35	6	0.00	0	109	Low
lake255	90.030	28.060	4381.61	0.075	1.13	1.13	1162	0	0.34	6	0.00	0	109	Low
lake256	90.035	28.058	4372.37	0.085	1.34	1.34	1270	0	0.34	6	0.00	0	109	Low
lake257	90.150	28.004	5003.11	0.152	3.03	1.82	1962	0	0.00	0	0.00	0	109	Low
lake258	90.142	27.992	4968.95	0.107	1.84	1.10	1506	0	0.00	0	0.00	0	109	Low
lake259	90.131	27.988	5049.94	0.204	4.57	2.74	2438	0	0.00	0	0.00	0	109	Low
lake260	90.149	27.986	4907.14	0.178	3.78	2.27	2205	0	0.00	0	0.00	0	109	Low
lake261	90.147	27.964	4878.19	0.236	5.61	3.37	2719	0	0.00	0	0.00	0	109	Low
lake263	90.259	27.925	5129.42	0.125	2.29	1.37	1689	0	0.40	0	0.00	0	109	Low
lake264	90.246	27.848	4800.28	0.113	2.00	1.20	1575	0	0.00	0	0.00	0	109	Low
lake265	89.917	28.116	4440.12	0.061	0.83	0.83	987	0	3.77	4	0.00	0	109	Low
lake268	90.320	27.985	5303.32	0.071	1.03	1.03	1108	0	7.15	0	0.00	0	109	Low
lake269	90.329	27.985	5274.29	0.076	1.14	1.14	1170	0	7.49	0	0.00	0	109	Low
lake271	90.533	28.170	5605.00	0.065	0.92	0.92	1041	0	0.00	0	0.00	0	109	Low
lake272	90.652	28.082	4999.86	0.207	4.67	2.80	2467	0	4.96	0	0.00	0	109	Low
lake277	90.803	27.895	5039.12	0.054	0.71	0.71	906	0	1.57	4	0.00	0	109	Low

Table S2. Distribution of GLOF exposed elements across local administrative unit and their danger ranking in Bhutan.

Local government administrative Unit	District	Area (km2)	Inundation area (km2)	People (count)	Building (count)	Bridge (count)	Road (km)	Farmland (km2)	Vulnerability Index	Danger Index	Danger level
Chhoekhor	Bumthang	1521.17	114.47	321	192	36	41.69	0.28	0.54	1.00	Very high
Punakha Town	Punakha	2.77	2.17	1635	272	4	10.84	1.14	0.44	0.57	Very high
Lunana	Gasa	1731.24	212.26	232	121	30	39.97	0.00	0.79	0.47	Very high
Thedtsho	Wangduephodrang	18.02	2.86	705	165	6	3.59	0.90	0.50	0.45	Very high
Bumthang Town	Bumthang	9.17	8.43	864	283	2	13.27	2.32	0.46	0.45	Very high
Khatoed	Gasa	286.04	2.65	16	17	4	0.42	0.00	0.57	0.42	High
Toedwang	Punakha	415.66	27.20	98	60	8	4.97	1.08	0.65	0.36	High
Nubi	Trongsa	556.42	40.11	53	29	8	1.95	0.30	0.58	0.35	High
Lamgong	Paro	48.99	2.53	541	195	6	7.86	0.85	0.48	0.30	High
Paro Town	Paro	5.27	2.55	1748	262	12	13.23	1.14	0.44	0.21	High
Darkar	Wangduephodrang	346.63	1.22	1936	85	16	3.22	0.31	0.53	0.20	High
Lingmukha	Punakha	33.80	1.36	90	65	2	5.74	0.19	0.62	0.18	High
Dzomi	Punakha	21.68	5.66	134	53	6	6.22	1.22	0.58	0.18	High
Wangdue Phodrang Town	Wangduephodrang	1.99	0.30	1059	109	0	1.19	0.25	0.45	0.16	Moderate

Local government administrative Unit	District	Area (km2)	Inundation area (km2)	People (count)	Building (count)	Bridge (count)	Road (km)	Farmland (km2)	Vulnerability Index	Danger Index	Danger level
Sharpa	Paro	80.20	2.27	370	120	8	3.75	0.94	0.50	0.14	Moderate
Toedtsho	Yangtse	48.97	0.33	20	13	0	0.39	0.09	0.69	0.13	Moderate
Athang	Wangduephodrang	778.41	2.57	54	38	10	2.04	0.42	0.67	0.11	Moderate
Khoma	Lhuentse	653.67	21.25	87	42	8	6.68	0.04	0.60	0.11	Moderate
Gase Tshogongm	Wangduephodrang	29.01	0.63	156	37	8	3.76	0.26	0.49	0.09	Moderate
Langthil	Trongsa	508.17	5.90	38	11	8	1.26	0.82	0.59	0.09	Moderate
Maenbi	Lhuentse	88.83	2.57	93	23	4	7.67	0.04	0.54	0.08	Moderate
Soe	Thimphu	177.87	2.14	43	21	6	4.82	0.00	0.67	0.07	Moderate
Laya	Gasa	966.98	27.03	35	13	28	12.43	0.00	0.68	0.07	Moderate
Yalang	Yangtse	89.77	5.25	15	9	6	0.91	0.46	0.68	0.07	Moderate
Guma	Punakha	34.84	2.71	158	78	2	2.37	0.53	0.53	0.07	Moderate
Gangzur	Lhuentse	533.72	6.88	33	13	8	13.47	0.05	0.62	0.06	Moderate
Kurtoed	Lhuentse	961.39	39.82	9	8	8	1.28	0.83	0.58	0.06	Moderate
Tangsibji	Trongsa	372.17	4.91	14	5	4	0.45	0.39	0.52	0.06	Moderate
Bapisa	Punakha	24.50	1.67	45	23	0	3.06	0.58	0.57	0.05	Moderate

Local government administrative Unit	District	Area (km2)	Inundation area (km2)	People (count)	Building (count)	Bridge (count)	Road (km)	Farmland (km2)	Vulnerability Index	Danger Index	Danger level
Tsento	Paro	579.54	5.79	63	23	30	9.01	0.14	0.48	0.05	Moderate
Ruebisa	Wangduephodrang	158.70	1.94	76	21	18	2.82	0.52	0.59	0.04	Low
Dopshar-ri	Paro	33.73	0.47	95	35	2	2.79	0.28	0.50	0.04	Low
Tingtibi Town	Zhemgang	0.55	0.13	78	22	2	0.09	0.01	0.45	0.03	Low
Saephu	Wangduephodrang	1107.98	103.84	1	1	4	14.21	0.00	0.62	0.03	Low
Loong-nyi	Paro	75.65	0.15	73	21	0	0.32	0.09	0.49	0.03	Low
Wangchang	Paro	16.13	0.77	35	17	2	0.41	0.40	0.49	0.02	Low
Duksum Town	Yangtse	0.42	0.01	40	10	2	0.05	0.00	0.54	0.02	Low
Samkhar	Trashigang	87.78	0.71	14	5	4	0.78	0.01	0.60	0.02	Low
Trashi Yangtse Town	Yangtse	2.86	0.14	69	19	4	1.20	0.05	0.44	0.02	Low
Korphu	Trongsa	290.21	1.12	8	3	2	0.26	0.02	0.67	0.02	Low
Ramjar	Yangtse	22.43	1.88	10	3	0	0.14	0.06	0.59	0.02	Low
Boomdeling	Yangtse	850.63	8.18	22	18	8	3.28	0.55	0.64	0.02	Low
Trong	Zhemgang	357.48	2.16	37	11	4	0.35	0.27	0.58	0.02	Low
Tongmajangsa	Yangtse	64.40	0.21	4	2	0	0.42	0.06	0.60	0.01	Low

Local government administrative Unit	District	Area (km2)	Inundation area (km2)	People (count)	Building (count)	Bridge (count)	Road (km)	Farmland (km2)	Vulnerability Index	Danger Index	Danger level
Chhubu	Punakha	90.94	4.91	8	4	12	4.47	0.95	0.61	0.01	Low
Rurichu Town	Wangduephodrang	0.24	0.07	47	6	0	0.09	0.02	0.48	0.01	Low
Goenshari	Punakha	88.39	0.66	10	5	4	0.37	0.01	0.63	0.01	Low
Khamdang	Yangtse	44.95	0.54	5	2	4	0.73	0.03	0.62	0.01	Low
Patshaling	Tsirang	136.45	0.99	10	1	4	0.82	0.08	0.60	0.01	Low
Tsaenkhar	Lhuentse	124.06	1.05	4	2	8	3.03	0.03	0.62	0.01	Low
Jarey	Lhuentse	137.86	0.53	14	1	0	0.05	0.01	0.69	0.01	Low