Supplemental Material for “Precipitation and aridity constraints from paleolakes on early Mars”

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1 ADDITIONAL DETAILS ON METHODS

In this section we describe the methodology behind the calculation of lake areas, lake volumes, and watershed areas. We also include additional details on the derivation of evaporation and precipitation expressions.

1.1 Lake area and volume measurements

We first calculated lake levels and their extents for each of the 96 lake systems using two related approaches for open- and closed-basin lakes. Closed-basin lakes did not fill up past the basin-confining topography (i.e., crater rims). As such, to determine the highest lake level the basin could host, we identified the highest MOLA contour that is contained entirely within each basin (see Goudge et al., 2015). To do this, we systematically evaluated contour lines within the lake basin by increasing them over 5 m intervals. Once a contour line crossed the crater rim and/or spilled into the surrounding topography, it was no longer contained and was considered breached. The lake contour level just prior to breaching is taken as the maximum lake level permitted (since breaching did not occur).

Open-basin lakes are characterized by their breached outlet canyons that formed once the basin accumulated enough water to fill and overflow. This constraint requires us to estimate the lake elevation contained in the basin before the breach existed. We used the same incremental contour evaluation technique as for closed-basin lakes (see above), except we ignored when contours breached into the existing outlet. Again,

once the contour line crossed the crater rim or spilled into the surrounding topography (ignoring the present breach), it was no longer contained and was considered breached. In contrast to closed-basin lakes, the lake contour level just prior to beaching is taken as the minimum lake level attained (since open-basin lakes did breach).

Once lake levels were estimated, they were used to determine lake area and volume. Lake area was measured directly from the lake contour using standard Esri ArcGIS measurement tools. For each individual lake we used a local equal-area (sinusoidal) projection with a central meridian located at the center of the basin. The lake volume corresponds to the volume contained between the lake level and the present-day topography of the basin. This was calculated by subtracting the MOLA dataset within the lake boundaries from the recreated lake water surface elevation. Note that even if basins are covered in up to 20 m of post-fluvial drape, this would only account for $< 10\%$ of measured volumes (avg. basin depth $\simeq 200$ m).

One important consideration is that the amount of evaporation changes with lake level, possibly providing a negative feedback as the lake area shrinks. As such, our measurements assume a temporally constant lake area. However, this potential feedback does not significantly impact our results. For open-basin lakes, we assume evaporation is zero, so that A_L is not factored in our precipitation estimates (note that $A_W + A_L$ remains constant). For closed-basin lakes, decreasing A_L (i.e., to account for the period of initial lake filling, when the lake area would have been smaller) would reduce evaporative losses, which would bring our maximums down.

1.2 Watershed area measurements

To determine watershed areas from MOLA elevation, we automated a flow routing model using the Hydrology toolbox in Esri ArcGIS. First, we used the Fill tool to remove local sinks (excluding the lake basin, which was masked out). We then used the Flow Direction tool followed by the Basin tool to automatically delineate drainage basins. Only watersheds draining into the crater lake were selected and merged in order to create the full inlet system watershed area.

Watershed areas were quality-checked against THEMIS and CTX images to ensure they represent dissected terrains and that their boundaries were in agreement with eroded valley network boundaries. If significant post-fluvial modification occurred, then the automatically extracted watersheds (which are representative of the present-day topography) would not match preserved inlet valley locations (e.g., due to visible tectonic deformation in the form of uplifted wrinkle ridges; Watters, 1991). For such watersheds we manually remapped the relevant section of the watershed boundary. Further, some watersheds extended beyond the visible valley network systems. For open-basin lakes, we left the extracted watershed as large as possible to make minimum precipitation more conservative. Conversely, for closed-basin lakes we clipped watershed areas to remove less definitive eroded regions where contribution to the lake was not certain; by including

the smallest extent possible we then make maximum precipitation estimates more liberal. We used the same local equal-area projection for watershed area calculations as we did for each individual lake area.

Note that where lakes are part of continuous lake chain systems (e.g., open-basin lakes fed by outlets of other open-basin lakes), we consider the entire watershed to include upstream crater lakes and their respective watersheds. For open-basin lakes, this works to increase watershed area, which further lowers the minimum precipitation. For closed-basin lakes being fed by upstream open systems, we more carefully quantified the depth of the breach relative to the basin depth to make sure we realistically maximized our precipitation estimates. If $> 90\%$ of the upstream lake volume breached it was included in the upstream watershed; otherwise, we excluded it. Additionally, some watersheds contain large craters that cannot easily be classified as either syn- or post-fluvial; as such it is not known whether the crater area contributed to the total watershed area during the basin-filling timescale. For watersheds of closed-basin lakes, these large craters were removed from the total watershed area, thus reducing the area. For open-basin lakes, these were included in the total area of the watershed, thus increasing the area. Again, this consideration works to lower the minimum precipitation and increase maximum precipitation.

1.3 Solutions to hydrological linear equations

To investigate the relationship between evaporation and precipitation for our lake systems, we can rewrite equation (1) in the following format:

$$E_T = \left(\frac{A_W + A_L}{A_L} \right) P_T - \frac{V_L}{A_L}. \quad (4)$$

Measuring A_W , A_L , and V_L for each system allows us to express the co-dependence of evaporation and precipitation for each basin as a linear function in the form $y = mx + b$. Because open-basin lakes give us a minimum V_L and closed-basin lakes give a maximum V_L , we obtain the inequalities:

$$E_T < \left(\frac{A_{W,O} + A_{L,O}}{A_{L,O}} \right) P_T - \frac{V_{L,O}}{A_{L,O}} \text{ (for open systems), and} \quad (5)$$

$$E_T > \left(\frac{A_{W,C} + A_{L,C}}{A_{L,C}} \right) P_T - \frac{V_{L,C}}{A_{L,C}} \text{ (for closed systems).} \quad (6)$$

These curves are individually calculated for each of the 96 lakes illustrated in Fig. 2A. As a result of the inequalities, open-basin lake curves provide an upper boundary, whereas closed-basin lake curves provide a lower boundary.

1.4 Deriving the aridity index, evaporation, and precipitation

Using the linear equations described above, we can solve for an aridity index (AI) value consistent with our entire dataset, which can then be used to find P_T values for each system, since $AI = P_T/E_T$. Aridity indexes plot as straight lines with slope = 1 in logarithmic space in Fig. 2A. All lake curves approach an asymptotic AI that equates to their $(A_W + A_L)/A_L$ value since the depth term, V_L/A_L , in equations (5) and (6) becomes negligible with increasing P_T . Within the open-basin lake dataset, open basin ID 182 has the lowermost curve since it has the largest lake area relative to its watershed area. This indicates that it is the open system that requires the most humid conditions to overflow. This constraint allows us to obtain a minimum global aridity index for our dataset, $AI_M = 0.26$, which would allow for every open-basin lake to breach, including open basin ID 182. AI_M is simply calculated as

$$AI_M = \frac{A_{L,O,182}}{A_{W,O,182} + A_{L,O,182}}, \quad (7)$$

using the geometries of open basin ID 182, and thus its curve is asymptotic to AI_M with increasing P_T in Fig. 2A.

To compare our results with previous work, we examine the ‘X ratio’ from a global hydrological routing model for open-basin lakes on Mars from Matsubara et al. (2011). They define this constant as $X = (E - P)/P$, which means that we can relate this to aridity index as $AI = 1/(X+1)$. They find that $0.11 < AI < 0.24$ (or $3.1 < X < 7.7$), although they use present-day topography in their model instead of recreating pre-breach conditions. Since they use present-day (post-breach) topography, they acknowledge that their lakes require less humid conditions (lower AI). This is consistent with our result since we observe our AI_M to be slightly larger than their estimated range. Note that to compare our estimates to theirs we assume that all precipitation on the watershed ends up as runoff (i.e., runoff fraction $R = 1$), which we discuss further below in Section 2.1.2.

The derived limits of AI can then be input into equation (1) to solve for the minimum and maximum precipitation for open- and closed-basin lakes, respectively. For open lakes, we used $E_T = 0$, and for closed lakes, $E_T = P_T/AI_M$, which result in equations (2) and (3). Graphically (in Fig. 2A), $P_{T,min}$ values are the asymptotic x-axis values for each open-basin lake curve (blue), whereas $P_{T,max}$ values are the intersection points between each closed-basin lake curve (red) with the AI_M dotted line in Fig. 2A. Using equations (2) and (3), precipitation limits were calculated for 72 out of the 96 mapped systems, since only closed systems for which A_L consists of $< 26\%$ of the total lake and watershed area ($A_L + A_W$) have solutions for $P_{T,max}$ (i.e., equation (3) becomes negative for large A_L). In total, 24 (out of 42) closed-basin lakes had no solution for $P_{T,max}$ (see Table S2). This is because precipitation is not bounded by this approach for large lake areas compared to their watersheds, i.e., $[A_{L,C}/(A_{L,C} + A_{W,C})] \geq AI_M$. In other words, no amount of precipitation

would cause these closed-basin lakes to breach given $AI = 0.26$. Graphically, this means that the curve for a closed-basin lake in Fig. 2A never intersects the AI_M dotted line. Finally, for Fig. 4A, instead of using the global minimum AI_M value, we calculated the minimum aridity for all open-basin lakes individually as

$$AI_{min} = \frac{A_{L,O}}{A_{W,O} + A_{L,O}}. \quad (8)$$

Note that the distribution of more humid locations in Figure 4A is analogous to regions with high $P_{T,min}$ in Fig. 3A. Although some clustering of high AI values may be apparent, because these are minimum values we do not assess the statistical significance of this clustering.

2 ADDITIONAL SENSITIVITY TESTS FOR RESULTS

In this section we consider different scenarios for the hydrological assumptions presented in the main text. Each different scenario results in a slightly modified frequency distribution illustrated in Figs. S3-6. Importantly, we note that none of the considerations below significantly modify our results.

2.1 Interbasin groundwater flow

While we do not explicitly include net groundwater losses, $G_{T,out}$, or gains, $G_{T,in}$, in our calculations, here we explore the implications for possible losses due to infiltration both from the watershed and the lake. We do not consider net gains because our topographically high paleolake population would likely have been groundwater recharge areas ($G_{T,in} \sim 0$), whereas large, low-lying basins such as Eridania basin were more likely to be groundwater discharge areas (Winter, 1999; Fassett and Head, 2008b). Below we consider infiltration losses in the lake and watershed separately.

2.1.1 Lake losses

First, on Earth, infiltration losses become less important with increasing aridity because intense, episodic P and E dominate the hydrological regime (see Fig. S2; Zekster & Loaiciga, 1993). Second, even if we explicitly add high infiltration ratios to our closed-basin lakes (e.g., $G_{T,out}/P_T \sim 0.5$ for rubbly basalts during a wet season in Idaho; Stephenson & Zuzel, 1981) results are largely unchanged (see Fig. S3). This is consistent with our first point: since evaporative losses are significantly larger than the precipitation, even for our highest AI value ($= 0.26$), there is minimal change in estimated precipitation. In this case, equation (3) would instead take the form

$$P_{T,max} = \frac{V_{L,C}}{A_{W,C} + A_{L,C}(0.5 - 1/AI_M)}. \quad (9)$$

Third, and perhaps most importantly, our method for determining the minimum aridity index (AI_M) aims to find the maximum amount of lake losses permitted in open-basin lakes. Although we express these losses as only evaporation, E_T , this term could in fact include any lake losses proportional to the extent of the lake. As such, the y-axis of our Fig. 2A could instead read ' $E_T + G_{T,out}$ (m)'. However, since it is likely that $E_T \gg G_{T,out}$, we simplify by considering only evaporation; this also allows us to express fractional precipitation losses (P_T/E_T) as a familiar term (i.e., aridity index, AI). As such, further lake losses due to infiltration (i.e., equation (9) and results in Fig. S3), in addition to the losses already accounted for in our AI term, are unlikely to affect lake hydrology.

2.1.2 Watershed losses

Although open-basin lakes provide a convenient way of limiting maximum possible fractional lake losses, the water fraction lost in the watershed remains unknown. For example, an analysis of the US Great Basin hydrology (which is comparable to that of Mars; Matsubara et al., 2011) during both present and Pleistocene conditions suggests that surface runoff only reached 50% of precipitation for portions of the drainage basin with yearly precipitation rates $P > 1$ m/yr, and only reached $\sim 80\%$ under Pleistocene conditions for $P > 2$ m/yr (Matsubara and Howard, 2009). One way to assess fractional losses in the watershed is to include a term, R , which describes the total amount of watershed precipitation that ends up as runoff and contributes to the lake volume. This results in a variation of equation (1), expressed as

$$V_L = RPA_W + PA_L - EA_L. \quad (10)$$

In the main text we assume $R = 1$. A value of $R < 1$ could occur due to any combination of i) evaporation from the watershed directly from any standing water, overland flow, or bedrock rivers, ii) ablation (e.g. sublimation) off accumulated snow volumes (if precipitation is nival in origin), and iii) interbasin infiltration (where groundwater does not flow back into the associated lake basin). The type of precipitation (pluvial vs. nival) is likely to affect R , since less runoff would be expected for snow due to the additional losses mentioned in (ii), in addition to those in (i) after melting occurs. Although impact gardening would have produced a fractured surface with high infiltration values, implying a reduced R on Mars, the development of duricrusts might also have enhanced runoff (e.g., Barnhart et al., 2009). Since a precise R value that characterizes the martian surface properties and climate is not available, we instead explore the dependence of $P_{T,max}$ on R , since a decreasing R would work to increase the amount of precipitation allowed in closed-basin lakes. However, a large R would also increase the minimum humidity (by increasing the required AI) required for open-basin lakes to overflow. Below we explore these two relationships and derive an expression for $P_{T,max} = f(R)$.

First, inclusion of watershed losses would affect our global AI_M value by modifying our equation (7):

$$AI_M = \frac{A_{L,O,182}}{R(A_{W,O,182}) + A_{L,O,182}}. \quad (11)$$

Note that open basin ID 182 would continue to be the most humid system irrespective of the value of R . Since equation (3) now takes the form

$$P_{T,max} = \frac{V_{L,C}}{R(A_{W,C}) + A_{L,C} - (A_{L,C}/AI_M)}, \quad (12)$$

we can rewrite equation (12) using the new expression for AI_M in equation (11) such that

$$P_{T,max} = \frac{1}{R} \times \frac{V_{L,C}}{A_{W,C} - A_{L,C} \left(\frac{A_{W,O,182}}{A_{L,O,182}} \right)}. \quad (13)$$

This suggests that $P_{T,max}$ is simply inversely proportional to R (i.e., $P_{T,max} \propto \frac{1}{R}$). This would mean that a value of $R = 0.5$, where only 50% of precipitation contributes to runoff, results in a doubling of maximum precipitation values (see distribution in Fig. S4). We also apply $R = 0.5$ to open-basin lakes in Fig. S4 to show that not only do absolute precipitation values only change moderately, but the relationship between both open and closed distributions remains largely similar. Note that an extreme value of $R = 0.1$, where 90% of precipitation is lost, would result in an order of magnitude increase in $P_{T,max}$ values.

2.2 Non-zero lake evaporation for open-basin lakes

To determine $P_{T,min}$ from open-basin lakes, we assumed that lake evaporation does not occur, in order to generate conservative minimums in the absence of known minimum evaporation estimates. Since this scenario is likely not physically plausible, we explored the effects on minimum precipitation if we maximize the evaporation, i.e., $E_T = P_T/AI_M$, for open-basin lakes. This recalculation results in a modified expression for equation (2) where

$$P_{T,min} = \frac{V_{L,O}}{A_{W,O} + A_{L,O} - (A_{L,O}/AI_M)}, \quad (14)$$

making our precipitation solution identical for both open- and closed-basin lakes. The modified distributions using this expression are shown in Fig. S5. Note that there is now overlap between the minimum and maximum precipitation distributions. This observation implies a spatially variable climate is required to satisfy all estimates. Critically, all coupled systems remain self-consistent such that $P_{T,min}$ is lower than $P_{T,max}$ within each system.

2.3 Closed-basin lakes and potential non-erosive outflows

We also explored the possibility that closed-basin lakes containing slight depressions on their rims could have overflowed but left no clear eroded outlet canyon. Closed-basin lakes that display this rim morphology are marked in Table S2 with an asterisk. Recalculation of precipitation distributions (assuming these were open-basin lakes instead) shows results are largely unaffected (Fig. S6).

3 SUPPLEMENTAL FIGURES

Figure S1: Schematic oscillating climate for early Mars (>3.7 Ga), with variable runoff production rate over time. Note that episodic runoff may be sourced from rainfall or snowmelt (e.g., Kite et al., 2013; Kite, 2019). (A) An open-basin lake breaches (= black arrow) if a given runoff episode, T , can i) supply enough liquid water (large runoff rate), and ii) be sufficiently continuous (long duration). Using open-basin lake geometries we can estimate minimum catchment-averaged precipitation integrated over this episode, $P_{T,min}$ (= blue hatched area). (B) Closed-basin lakes never breach; thus, we can estimate maximum catchment-averaged, time-integrated precipitation, $P_{T,max}$ (= red hatched area), for any given runoff episode. Note that to erode the deep valley networks which feed these systems, water volumes greatly exceeding lake volumes are required, suggesting multiple runoff events likely occurred.

Figure S2: Relationship between aridity index and relative groundwater contribution on Earth. Black circles = data for different continents (Zekster & Loaiciga, 1993); dashed line = best-fit line; white circle = Earth average. Note location of estimated minimum global Mars aridity AI_M (red arrow). Terrestrial data were obtained using extensive analyses of precipitation, latent heat (or direct evaporation), and runoff data from all the continents.

Figure S3: Frequency distribution of precipitation values if groundwater losses are added to closed-basin lakes. Blue/red = open-/closed-basin lakes ($n = 54/15$); blue/red dotted lines (and triangles) = best-fit logarithmic normal functions for open-/closed-basin lakes (and logarithmic means). White bars = recalculated precipitation ranges for coupled systems. Gray dotted line = best-fit function for closed-basin lakes (no infiltration) from Figure 2B. Gray-outline bars = precipitation ranges for coupled systems from Figure 2B.

Figure S4: Frequency distribution of precipitation values if we assume runoff fraction $R = 0.5$. Blue/red = open-/closed-basin lakes ($n = 54/18$); blue/red dotted lines (and triangles) = best-fit logarithmic normal functions open-/closed-basin lakes (and logarithmic means). White bars = recalculated precipitation ranges for coupled systems. Gray dotted lines = best-fit functions from Figure 2B (no watershed loss). Gray-outlined bars = precipitation ranges for coupled systems from Figure 2B.

Figure S5: Frequency distribution of precipitation values if AI_M is used to constrain evaporation for both open- and closed-basin lakes. Blue/red = open-/closed-basin lakes ($n = 54/18$); blue/red dotted lines (and triangles) = best-fit logarithmic normal functions open-/closed-basin lakes (and logarithmic means). White bars = recalculated precipitation ranges for coupled systems. Gray dotted line = best-fit function for open-basin lakes ($E=0$) from Figure 2B. Gray-outlined bars = precipitation ranges for coupled systems from Figure 2B.

Figure S6: Frequency distribution of precipitation values if only maximum confidence closed-basin lakes are considered. Blue/red = open-/closed-basin lakes ($n = 65/14$); blue/red dotted lines (and triangles) = best-fit logarithmic normal functions open-/closed-basin lakes (and logarithmic means). White bars = recalculated precipitation ranges for coupled systems. Gray dotted lines = best-fit functions (considering original closed-basin lakes) from Figure 2B. Gray-outlined bars = precipitation ranges for coupled systems from Figure 2B.

4 SUPPLEMENTAL TABLES

Table S1: Morphometric measurements, derived minimum precipitation, and minimum aridity index of 54 valley network-fed open-basin lakes on Mars (where $P_{T,min} = V_{L,O}/[A_{L,O} + A_{W,O}]$, and $AI_{min} = A_{L,O}/[A_{L,O} + A_{W,O}]$).

Basin ID	Latitude (°)	Longitude (°)	Lake Area, $A_{L,O}$ (km ²)	Lake Volume, $V_{L,O}$ (km ³)	Watershed Area, $A_{W,O}$ (km ²)	Min. Precipitation, $P_{T,min}$ (m)	Min.Aridity Index, AI_{min}
<i>Goudge et al. (2016):</i>							
6	-11.5	152.8	7267.8	1183.3	110792.9	10.0	0.061
7	-12.4	157.1	409.7	76.3	186360.1	0.4	0.002
16	-21.7	-12.3	24325.4	6139.3	167178.4	32.1	0.127
19	-10.6	2.8	22170.6	11007.5	495706.8	21.3	0.043
26	-4.6	90.0	284.5	54.9	15785.2	3.4	0.018
32	-23.1	-23.5	2085.0	240.8	123543.0	1.9	0.017
37	10.0	31.6	25724.0	3898.2	1339827.5	2.9	0.019
38	1.3	35.5	2049.0	553.4	960010.4	0.6	0.002
39	-6.4	42.0	994.0	135.8	68381.1	2.0	0.014
43	19.0	35.1	3010.1	581.8	599699.3	1.0	0.005
45	18.4	77.7	1484.8	424.0	31022.2	13.0	0.046
46	-10.3	127.2	60.8	2.6	3609.2	0.7	0.017
47	-10.4	128.0	84.1	6.3	542.6	10.1	0.134
48	-7.3	131.1	482.8	60.4	7870.5	7.2	0.058
63	-0.8	125.2	185.9	29.7	4410.3	6.5	0.040
64	-1.6	126.6	199.0	11.7	6122.2	1.9	0.031
72	-9.4	134.9	2023.6	892.9	38574.3	22.0	0.050
81	-4.2	-1.7	1125.0	161.8	12471.1	11.9	0.083
84	-20.5	87.0	638.2	105.4	22745.1	4.5	0.027
90	-20.0	170.7	567.8	46.4	5577.1	7.6	0.092
95	-22.5	-20.5	596.7	14.7	4959.5	2.7	0.107
96	-29.8	147.2	201.2	11.9	4501.2	2.5	0.043
130	-12.0	-177.9	346.8	130.9	18314.7	7.0	0.019
137	-26.1	85.4	68.8	5.8	26292.4	0.2	0.003
139	0.0	28.8	3032.7	956.1	405168.2	2.3	0.007
147	-26.5	-4.0	86.3	8.5	17457.9	0.5	0.005
149	-10.0	41.1	372.8	26.8	37558.8	0.7	0.010
150	-9.0	41.5	961.8	218.0	40215.3	5.3	0.023
154	-18.7	174.9	333.5	35.4	8456.5	4.0	0.038
155	-11.6	-159.6	856.7	81.6	91202.3	0.9	0.009
162	-35.7	-44.6	358.9	15.1	9108.5	1.6	0.038
164	-11.2	15.7	343.2	31.1	4050.3	7.1	0.078
166	-6.4	24.4	1205.3	101.9	4963.7	16.5	0.195
167	-27.1	142.1	587.7	65.3	1897.8	26.3	0.236
171	-21.3	-5.3	51471.4	7549.4	176743.1	33.1	0.225
174	-10.7	132.5	146.2	5.0	427.7	8.7	0.255
175	-22.0	132.5	221.5	17.1	2221.3	7.0	0.091
182	-5.6	57.3	264.8	13.9	760.6	13.6	0.258
185	2.2	45.5	153.0	12.1	1347.9	8.0	0.102
186	0.5	42.9	158.1	11.1	684.2	13.2	0.188
187	-7.2	43.0	672.6	70.8	2693.9	21.0	0.200
210	-5.1	-4.5	43.5	2.4	940.6	2.5	0.044
<i>This study:</i>							
226	-29.8	-77.1	57.1	3.2	7671.4	0.4	0.007
227	-22.0	89.6	68.1	4.0	1330.0	2.8	0.049
228	-8.8	33.2	209.7	29.0	911.2	25.8	0.187
229	-6.4	23.9	18.6	0.9	962.4	1.0	0.019
230	0.9	36.0	98.5	9.1	2082.9	4.2	0.045
231	7.8	47.8	71.3	2.2	922.6	2.2	0.072
232	-4.1	21.8	227.9	37.3	3041.1	11.4	0.070
234	-10.1	128.4	85.9	7.0	1191.7	5.5	0.067
236	-7.4	59.5	134.6	5.2	6113.1	0.8	0.022
237	-4.4	88.4	42.2	3.5	835.7	4.0	0.048
238	-25.3	138.3	392.6	31.4	3236.0	8.7	0.108
239	-24.6	149.0	760.9	34.2	7191.6	4.3	0.096

Table S2: Morphometric measurements and derived maximum precipitation of 42 valley network-fed closed-basin lakes on Mars (where $P_{T,max} = V_{L,C}/[A_{W,C} + A_{L,C} - (A_{L,C}/AI_M)]$, with $AI_M = 0.26$).

Basin ID	Latitude (°)	Longitude (°)	Lake Area, $A_{L,C}$ (km ²)	Lake Volume, $V_{L,C}$ (km ³)	Watershed Area, $A_{W,C}$ (km ²)	Max. ^a Precipitation, $P_{T,max}$ (m)
<i>Goudge et al. (2016):</i>						
8	-3.3	88.3	2159.3	393.9	9585.5	116.4
9	-5.8	42.8	937.3	181.2	2951.9	698.1
13*	-8.3	128.7	10474.5	3158.3	50095.7	157.8
15*	-13.3	176.6	674.0	242.1	1222.9	-
17*	-15.2	61.3	378.9	16.0	1483.2	40.6
18	-18.8	59.2	5940.0	3007.0	7212.3	-
19	-19.4	52.0	1738.5	537.5	11489.3	82.7
59	17.7	3.8	975.7	268.9	909.0	-
68	10.6	39.5	1207.2	208.6	1601.7	-
87	3.1	35.2	1411.1	500.1	1671.5	-
89	3.0	45.5	1195.7	331.6	3752.8	1041.9
115	-11.3	131.4	6603.7	2493.3	4651.8	-
132	-16.2	45.9	382.5	78.1	1427.4	237.6
139	-19.5	-13.3	1382.0	826.4	885.9	-
140	-19.9	-2.9	3437.4	1464.4	10626.5	1944.4
142	-19.4	53.8	562.7	250.5	5234.6	69.2
157	-27.3	127.7	248.3	73.6	862.7	492.7
158	-25.7	97.5	213.4	125.8	2755.7	58.7
165	-31.5	128.3	277.4	44.1	1412.6	71.6
203	-24.0	-33.3	1684.0	525.5	8070.3	162.5
<i>This study:</i>						
206	-15.5	50.8	1085.7	64.1	2350.6	-
207*	-2.2	103.4	662.9	96.8	1355.3	-
208	-0.7	100.0	2973.7	606.3	6886.5	-
209	-11.8	88.3	371.0	93.2	2193.1	82.6
210	-4.3	46.8	822.1	132.3	1302.4	-
211*	-17.2	-17.9	234.4	27.0	624.6	-
212*	-19.2	130.3	7050.6	3112.6	3316.5	-
213	-21.2	128.8	29568.1	6937.2	68308.5	-
214*	-12.2	63.6	61283.0	7829.2	60075.2	-
215	-7.7	56.4	47612.3	9217.4	117904.0	-
216*	11.2	47.3	16423.2	1999.1	75752.5	69.9
217	5.9	30.6	2094.8	798.1	1933.2	-
219*	-27.6	138.7	20171.0	5898.4	27117.2	-
220	-30.1	149.7	13702.7	1831.7	56800.7	105.0
221	-44.0	143.3	1595.7	675.2	6200.8	417.4
222*	-7.7	68.9	4099.7	267.0	19758.8	33.5
223	8.5	52.4	7067.2	727.2	12065.6	-
224	-29.4	144.2	60363.8	10442.4	128585.4	-
225	-22.4	145.7	3470.0	2698.9	1359.5	-
226*	-5.6	52.6	1595.9	417.9	3493.9	-
227	-22.4	145.7	1191.2	562.5	1872.2	-
229	0.4	45.1	14814.6	7044.8	3375.0	-

^a: Note that precipitation is not bounded by this approach for systems with large lake areas compared to their watersheds, i.e., $A_{L,C}/(A_{L,C} + A_{W,C}) \geq AI_M (= 0.26)$.

*: Closed-basin lakes containing slight topographic depressions on their basin-confining crater rims. It is possible that these systems overflowed slightly at these notches in the crater rim; however, they display no clear evidence of an incised outlet canyon (Fig. S4).

Table S3: Key for 13 coupled lake systems and calculated precipitation ranges on Mars (see Tables S1 and S2 for reference).

Open Basin ID	Closed Basin ID	Coupling Type ^a	$P_{T,min}$ (m)	$P_{T,max}$ (m)
16	139	Embedded	32.1	-
187	9	Embedded	21.0	698.2
231	216	Adjacent	2.2	69.9
171	140	Embedded	33.1	1944.4
237	8	Adjacent	4.0	116.4
47	13	Embedded	10.1	157.8
185	89	Embedded	8.0	1041.9
182	215	Embedded	13.6	-
238	219	Embedded	8.7	-
96	220	Embedded	2.5	105.0
234	224	Embedded	5.5	-
37	218	Embedded	2.9	-
167	207	Adjacent	26.3	-

^a: Coupled systems are sub-classified as either an open-basin lake located within the watershed area of a closed-basin lake (embedded; see Fig. 1C), or open- and closed-basin lakes that share drainage divide boundaries (adjacent).

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