Introduction: Martian paleolakes offer a convenient setting for mass- and energy-balance calculations to constrain the past hydrology and water source [1,2]. Eberswalde crater is particularly useful in this regard due to its relict delta [3–7] that reflects the water level in the crater. Here we use the dominant discharge estimated from inverted-channel width and meander geometry, the area of the paleolake and contributing watershed, and energy requirements for lake evaporation to constrain the mean annual runoff production and water source. Given the maximum age of the delta based on crater counts on Holden ejecta [8], these results suggest a discrete post-Noachian interval of fluvial erosion on Mars.

Age of the Eberswalde Delta: Although Eberswalde crater is older than the adjacent Holden crater, the Eberswalde delta post-dates the Holden impact and superimposes its ejecta [4,8], which provide a larger surface area for crater counts. The superimposed crater population >1 km in diameter indicates a Late Hesperian age for Holden crater, with error bars that range within the Early and Late Hesperian Epochs [8]. The Eberswalde delta is thus Hesperian or younger and post-dates Noachian valley networks. Hesperian or later fluvial activity also occurred at Gale crater, Aeolis Mensae [9], the Valles Marineris region [10–12], and other areas on Mars [13].

Estimates of Dominant Discharge: Two well-preserved meander loops on the Eberswalde delta have relationships between inverted-channel width and measures of meander geometry that are consistent with terrestrial meandering rivers [14]. Previous studies have used empirical relationships between discharge and channel dimensions or a model of alluvial fan formation, all scaled for Martian gravity, to estimate dominant discharge ranging from 410 to 700 m$^3$/s [4,15,16].

In Equations 1 and 2, $Q_x$ is the dominant discharge (m$^3$/s), which has a recurrence interval of $x$ years in the settings where the relationships were derived; $W_b$ is bankfull width; and $\lambda_m$ is meander wavelength. The northern and southern meanders (the latter is shown in Fig. 1) reflect different channel-forming discharges, although their stratigraphic positions on the delta are consistent with a roughly similar age. Results for the northern meander are 460 and 390 m$^3$/s, and those for the southern one are 140 and 180 m$^3$/s using equations 1 and 2, respectively. These results are broadly consistent with previous studies [4,15,16].

Event Runoff Production: Given a dominant discharge for the northern channel of 460 m$^3$/s, the event runoff production would be about 3 mm/day from a topographically defined watershed of 12,500 km$^2$ or about 8 mm/day from the 5000 km$^2$ crossed by mapped valleys. These values correspond to (perhaps significantly) higher rates of precipitation or melting, likely in excess of 1 cm/day at times, given losses to evaporation and infiltration from the watershed surface. The rates for the southern channel are about a third of those for the northern one.

Lake Evaporation: Evaporation from the 400-km$^2$ lake would be highest for a perennially ice-free lake and lowest for a frozen one. An energy-balance approach can be used to estimate the evaporation rate $E$ (m/s):

$$E = (K + L - G - H + I - \Delta Q/\Delta t) / \rho v,$$  

where $K$ is net shortwave radiation input (the variables in parentheses are all J/m$^2$s), $L$ is net longwave radiation input, $G$ is energy conduction to the ground, $H$ is sensible heat loss to the atmosphere, $I$ is net input of energy from inflows, $\Delta Q$ is the net change in stored
heat over time $\Delta t$, $\rho$ is the density of water (1000 kg/m³), and $\nu$ is the latent heat of vaporization (2,260,000 J/kg) [17]. We assume a constant water temperature ($AQ = 0$), and energy exchange with the ground ($G$) is typically negligible. Thus, without significant heat input from a hot atmosphere ($L$ and $-H$), the energy available to evaporate inflowing water is limited to excess heat in the contributing stream and net shortwave radiation, which is <160 W/m² averaged over 24 hours. The former ($I$) is small for a cold river but rises to 76 W/m² at 25°. Adequate energy was available to evaporate at most two or three meters of water per year from the lake, if the lake remained unfrozen and the entire energy budget was used for evaporation, but lower rates are more likely.

**Water Source:** Hypotheses for the Eberswalde water source include impact-generate runoff and some kind of atmospheric water cycle. Both hypotheses imply a limited lifetime for the lake.

Melting of pre-existing ice by hot ejecta from the Holden impact would produce a single continuous but declining discharge, of which the inverted channels on the delta surface represent a late-stage minimum. Continuous flow at 290 m³/s (the average of four estimates) would require 23 m/year of evaporation from the lake surface, an order of magnitude more than the energy budget allows.

Precipitation of snow onto hot, fresh ejecta would require relatively high precipitation and melting rates to generate runoff, due to the need to offset infiltration into the ejecta, which typically has a high infiltration capacity [18]. Water that entered the lake as groundwater rather than through the surface stream would also need to be evaporated, but highly intermittent runoff might offset this excess supply within the energy budget.

Another alternative is ephemeral runoff production through rain or snow melted by insolation. To offset evaporation of 0.1–1 m/yr from the 400-km² lake, intermittent precipitation of >1 cm/day (some of which would infiltrate or evaporate from the watershed) and runoff production of ~0.8–8 cm/year would be required. To form a delta of ~6 km³ [3] at a reasonable water-to-sediment volume ratio of 100:1, these conditions would have persisted for ~10³–10⁴-year timescales. The Eberswalde delta did not require a very wet climate (in fact, it appears to disallow one), but intermittent runoff production was significant at times. This rough duration falls within the wide range suggested by prior workers, <10³ years [15] at one extreme and >10⁵ [5] at the other.

**Interpretation:** These results suggest that peak conditions for Martian runoff may have resembled an arid terrestrial desert, and that conditions outside of wetter intervals were hyperarid by terrestrial standards (although perhaps not as dry as modern Mars). Previous studies introduced the concept of an intermittent water cycle and multiple generations of valley development on early Mars [e.g., 10,19–21], although means to activate and deactivate the water cycle remain conceptual. The need to liberate the Martian water inventory from topographic and thermal traps in the highlands, poles, and subsurface suggest that ideal conditions for polar melting (high obliquity, perihelion summer) under a thicker early atmosphere may have been favorable.

**Implications for Mars Science Laboratory (MSL) Site Selection:** The relatively young age of fluvial to lacustrine deposits in Eberswalde and Holden craters is likely related to the excellent preservation of their stratigraphy, relative to older Noachian materials. Moreover, these deposits record an interval of time when liquid water was abundant, in contrast to drier conditions that prevailed throughout most of Martian history, outside of geologically discrete periods of valley network development.

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**References:**