Modeling the hydrological evolution of Jezero's crater lake and its deltaic deposit

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Introduction:

Jezero crater, the landing site of the Perseverance rover, once hosted a lake (Fassett and Head, 2005; Schon et al., 2012; Goudge et al., 2015). Understanding its evolution over time is essential to improve our knowledge of ancient hydrologic activity on Mars.

A recent study by Villette et al. (2025) showed that Jezero was mainly a closed-basin lake, which overflowed at least four times on its eastern rim over a short period of time, responsible of the formation of Pliva Vallis, the outlet valley. This work, briefly detailed below helped to constrain part of Jezero's hydrological history but key questions remain regarding the time scales and processes involved in the lake's infilling and its final evolution. Thus, we seek to determine (i) how and how quickly the lake filled, and (ii) how long it took to deposit the western delta during the final drying out of the lake.

Observations of the delta stratigraphy, carried out by Perseverance, show a progradation of sediments, as well as a decrease in the elevation of the topset – foreset transitions towards the interior of the crater (Mangold et al., LPSC 2024). These observations provide valuable constraints to estimate the duration and dynamics of sediment deposition during the lake drying out. To constrain the timing and the processes of lake filling/drying out and delta formation, we develop a numerical model that integrates hydrological and climatic inputs with sediment transport dynamics.

A study of Pliva Vallis (Villette et al., 2025):

Observations: The presence of Pliva Vallis, raises the question of whether the lake system operated as an open basin, or as a closed basin system with one or more overflow events. To tackle this uncertainty, we performed a detailed morphological study of Pliva Vallis. Its atypical morphology, along with the presence of re-incised fluvial deposits, perched valleys and bedrock incision terraces (Figure 1) led us to interpret this valley as a discontinuous and temporary overflow valley, progressively carved by four distinct breach episodes.

Modeling results: To provide a minimum estimate of the duration of these four episodes, we used a 0-D model, simulating valley formation by breach erosion. Results suggested that each flooding and incision of Pliva Vallis would have occurred in less than a few weeks, or even a few days for some episodes.

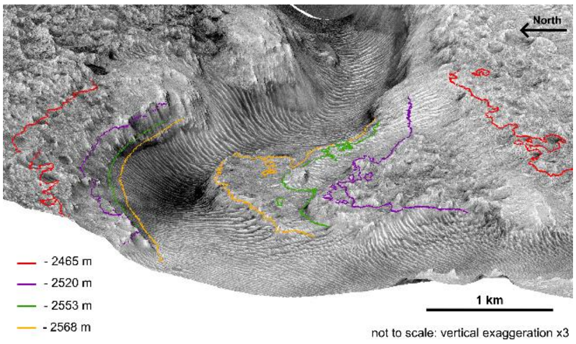

Figure 1: 3D representation (HiRISE image over a DTM) of Pliva Vallis where the four incision terraces were identified. Each colored line identifies the elevation of these terraces.

Delta formation and lake drying out:

The next step of this work is to constrain the initial filling of the lake and the deposition of the western delta during the drying out. To do this, we perform a numerical modeling of the temporal and hydrological evolution of the Jezero crater lake, considering all water inputs (surface runoff via Neretva Vallis, groundwater inflow, direct precipitation on the lake) and outputs (evaporation, infiltration, outflow through Pliva Vallis) in the system.

The aim of this work is to model two distinct phases of the lake's history: (i) its initial infilling (V = 450 km^3) up to a lake elevation of -2243m and (ii) the progressive deposition of the 2.5 km^3 delta on the western edge of the crater during the lake's final drying out between the lake levels of -2390 and -2500 m (where 240 < V < 110 km^3, Figure 2).

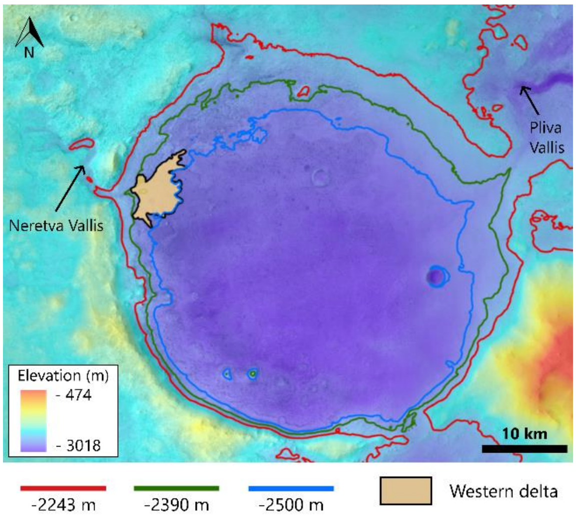

Figure 2: Map of the Jezero crater, its outlet Pliva Vallis, its inlet Neretva Vallis and the western delta. Colored contour lines represent water elevations in the lake at different stages of the evolution of the lake.

Our numerical model considers the intermittency of inflows via Neretva Vallis and outflows via evaporation, as well as interannual climate variability throughout the simulation. We assume that hydrological inputs are caused by a glacier or snowpack melt upstream of Neretva Vallis (Figure 3). The volumes and discharges produced by melting are estimated using a Degree Day Model: for each positive degree each day, a given thickness of glacier or snowpack melts. Temperature data used in our model come from a climate model published by Kite et al. (2022). We check that the calculated discharges are consistent with the granulometric observations of deltaic strata made by Perseverance, and within the ranges of flows estimated by the recent work of Mangold et al. (2024; ranging 120 to 520 m3/s).

From these water discharges, sediment fluxes are then calculated using the relationship between channel geometry and water discharge proposed by Konsoer et al. (2018) and the empirical sediment transport equations established by Kleinhans (2005). Evaporation rates are derived from GCM outputs (surface temperature, atmospheric temperature and wind velocity), enabling a volume balance of inflows and outflows to estimate the evolution of the lake volume over a Martian year.

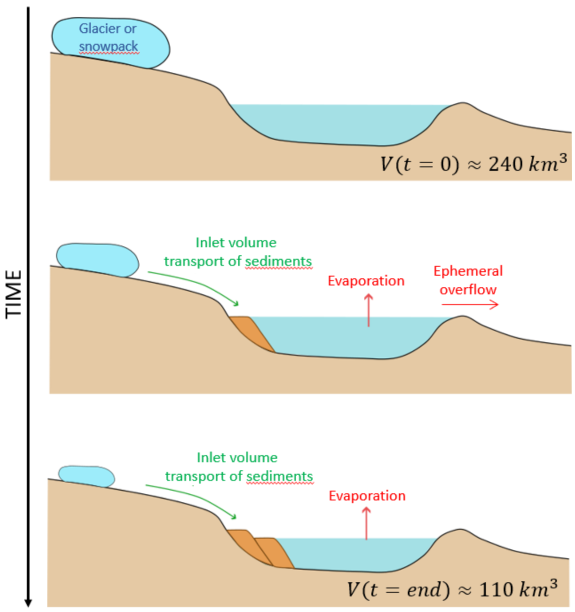

Figure 3: Sketch of the evolution of water input into the lake from glacier or snowpack melt and of delta deposition during the lake drying out, made possible by significant evaporation.

Delta formation and lake drying out: results and possible scenarios

We tested several different models, ranging from a simple model with no climatic intermittency to a complex model considering (i) climatic intermittency, (ii) intermittency of inflows and outflows, and (iii) the decreasing size of the glacier/snowpack.

Preliminary modeling results are promising. They show that it is possible to simulate climatic and hydrological conditions in which the lake infills quickly (several hundred years), involving a limited volume of sediments, representing less than 25% of the current delta volume deposited during the drying out. These results are consistent with observations which suggest the visible part of the delta is dominated by progradation, and was not established in the early stages during the lake level rise (Mangold et al., LPSC 2024).

Delta formation simulations show that there are climatic and hydrological conditions where the 2.5 km^3 of the delta can be deposited over a timescale similar to that required to empty the lake down to the last topset - foreset transition. The timescales involved in this phase are on the order of a few thousand years. The results also show that, under certain modeled conditions, it is important to consider the recharging of the glacier or the snowpack over time.

By combining the results of the simulations of lake filling and delta deposition during the emptying, we identify two main scenarios for the lake's evolution:

- *Scenario 1*: (i) the lake initially fills with either groundwater or a glacial surge (not modeled here), (ii) the lake breaches and overflows in at least four rapid episodes, (iii) the delta forms from sediments transported by meltwater from a stationary glacier upstream of Neretva Vallis and evaporation from the lake is enough to compensate for the water inflow and progressively decrease the lake level.

- *Scenario 2*: (i) the lake initially fills with water produced by the melting of a glacier or a snowpack that gradually decreases in size, (ii) the lake breaches and overflows in at least four rapid episodes, (iii) the delta forms from sediments transported by meltwater from a glacier or snowpack, that needs to be recharged, and evaporation from the lake is enough to compensate for the water inflow and progressively decrease the lake level.

The two scenarios proposed above can both explain the assumption of quick lake filling and the delta formation during lake drying out, over a timescale of a few thousand years. It is important to note that other conditions that are not simulated here might work too.

To discuss our results, we are aware that our numerical model relies on another model (GCM from

Kite et al., 2022) which provides important input parameters. However, this work proposes a more realistic approach than previous studies which either assumed stationary fluxes without climatic and hydrological intermittency (Salese et al., 2020; Horvath and Andrews-Hanna, 2024), or applied artificial intermittence parameter (Lapôtre et al., 2020). Therefore, our study constitutes a robust starting point to propose a realistic numerical model of Jezero's hydrology and its evolution over time.

Conclusion:

Our numerical model allowed us to simulate the hydrological evolution of the Jezero's crater lake. This work enabled us to proposed realistic scenarios that can explain observations and consequently the history of the lake and its delta.

Our results support a three-phase evolution scenario for the Jezero crater lake: (i) quick infilling in a closed system, (ii) four episodes of breach overflow and Pliva Vallis incision, (iii) delta deposition in a closed system during the gradual drying out of the lake over several thousand years.

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