HYDROLOGY OF EARLY MARS: RELATIVE CHANNEL DISCHARGES FROM DEPTH OF VALLEY NETWORK INCISION. Y. Matsubara, J. P. Gochenour and A. D. Howard, Department of Environmental Sciences, University of Virginia, P.O. Box 400123, Charlottesville, VA 22904-4123 (ym9z@virginia.edu).

Introduction: Valley networks incised up to several hundred meters into the cratered highlands are ubiquitous on the equatorial cratered highlands. Incision required streamflow from precipitation occurring as direct runoff, snowmelt, or groundwater discharge. The majority of the valley networks ceased to erode about the Noachian-Hesperian boundary, although some valley systems were episodically active until about the Amazonian-Hesperian boundary. The valley activity near the Noachian-Hesperian boundary may have resulted from a relatively brief climatic optimum. The width and meander wavelength of locally-preserved channels within the valley networks suggest formative discharges reached magnitudes equivalent to the mean annual flood in terrestrial drainage networks with the same contributing area.

The climatic conditions responsible for valley network incision remain uncertain. Simulations of early Martian climate to date have been unable to replicate conditions conducive to an active hydrologic cycle, due to the ease of escape of volatiles due to the lower Martian gravity and the early loss of the magnetic field as well as the lower luminosity of the early Sun. Energy additions from large impacts short-term enhancement of greenhouse gases due to volcanism have been suggested as causes of short-duration warmer climates.

Methodology: We are constraining the early hydrologic cycle on Mars through analysis of paleolakes and depths of valley incision. The absolute magnitudes of precipitation, runoff, and evaporation on early Mars are uncertain, but evidence from overflowing lakes and relative amounts of channel incision can constrain the ratio of these quantities, the X-Ratio:

\[ X=\frac{(E-P)}{RP} \]  

Here \( E \) is the yearly depth of evaporation from lakes, \( P \) is yearly depth of precipitation, and \( R \) is the fraction of precipitation on highlands that enters the channel system through overland flow, throughflow, and groundwater seepage. Low X-Ratios imply humid conditions, and high values reflect desert-like settings. Terrestrial settings with throughflowing drainage generally have X-ratios between +1 to zero. Hot deserts such as in the Great Basin can experience X-ratios exceeding 20. During the last glacial maximum when large lakes (e.g., Bonneville and Lahontan) occupied the Great Basin X-ratios dropped below 4 [4].

Results from Analysis of Overflowing Lakes: Using a MOLA-derived digital elevation model we have simulated the relative distribution and sizes of lakes and channel discharges for a wide range of assumed X-Ratios [1]. Our initial analysis focused on determining the value of the X-Ratio that must have occurred in order to create channelized exit breaches in some basins. The majority of exit-breach basins required X-ratios between 3 and 6 to overflow, although there is some regional variation in the required X-ratio. These estimates may over-estimate the required X-ratio because the exit breaches have lowered the required lake levels necessary for overflow. That is, more humid conditions and lower X-ratios may have been required for the initial basin rim breaching.

Relative Depths of Channel Incision: The relative amounts of valley network incision provide an additional constraint on the hydrology of early Mars. The rate of bedrock channel incision is commonly modeled as a function of flow intensity, such as shear stress or stream power [2]. Through the use of formulas for flow resistance and channel dimensions, the incision rate, \( I \), can be expressed as a function of local channel gradient, \( S \), and a characteristic discharge, \( Q \) (such as the mean annual flood):

\[ I = K Q^{m} S^{n} \]  

where \( K \) is a constant dependent on flow frequency and intrinsic bedrock erodibility, and \( m \) and \( n \) are exponents that can be theoretically derived or empirically estimated. If a region experiences an areally uniform climate then the depth of incision can be correlated with estimated discharges and channel gradients to estimate the constant and exponents in the above relationship. As part of the present effort representative martian cratered highland valley networks have been digitized. Local estimates of the depth of valley incision can be made from the difference between the elevation of the valley bottom and the elevation of the surrounding uplands as discussed by [3].

In most terrestrial drainage networks lakes are rare and the discharge, \( Q \), can usually be expressed as a simple power function of upstream contributing drainage area. On Mars, however, drainage integration was poor because of interspersed depressions, mostly due to impact craters. Thus parts of the potential upstream drainage area might not actually contribute to streamflow because evaporation in lakes occupying basins causes lakes not to overflow into downstream basins (Fig.1a). Thus the channel-forming discharge would be less than the discharge that would result when all potential upstream area contributes to the flow (Fig.1b). Figure 2 shows the relative discharge averaged for a number of valleys in the Isidis region of
Mars expressed as a ratio of the simulated discharge for a given X-Ratio to that which would occur if all potential upstream areas fully contributed to the flow. For an X-Ratio of -1 all areas do contribute (evaporation, \( E = 0 \) and the runoff coefficient, \( R = 1 \)) so that the relative discharge is 1. As the X-Ratio increases, evaporative losses increase and/or the runoff coefficient decreases which causes the relative discharge to decrease. For integrated terrestrial drainage networks the relative discharge drops more gradually over the range of the X-Ratio we used (Figure 2). Thus Figure 2 shows that for large X-Ratios portions of the potential contributing area in the Isidis region would become inactive because of evaporative losses.

An expression of the type of Eq. 2 was fit by least-squares regression to 45 stream reaches in the Isidis region using estimated incision depth, \( I \), reach gradient, \( S \), and relative discharges, \( Q \), estimated from hydrologic simulations for 15 specific assumed values of the X-Ratio ranging from -1 to 14. The 45 reaches were chosen to sample a wide range of local stream gradient and potential upstream contributing area. The relative success of Eq. 2 in estimating incision depths can be expressed as the regression \( R^2 \) value. The relative role of estimated discharge, \( Q \), in the regression can be measured by the “t” statistic for the estimated exponent, \( n \), with higher values indicating greater significance (Figure 2).

Both the \( R^2 \) values and the “t” statistic suggest that the best fit for incision depths occurs for low values of the assumed X-ratio (Figure 2), specifically for X-ratios less than 2. Drainage in the Isidis region is well-integrated with few undrained basins, suggesting extensive erosion and a relatively wet climate. The estimated X-ratios from breached lakes in the Isidis region are also relatively low, about 4.2 [1].

Discussion: We are collecting incision depth data for several regions on the highlands of Mars (mainly in the area between 30 °N and 40 °S) to do a similar analysis using Eq. 2. This should reveal regional variations in the degree of precipitation and evaporation during formation of the valley networks and will supplement our regional analysis from breached lakes [1]. In addition to finding which value of the X-ratio best explains spatial patterns of incision depths, regional variations in the fitted multiplicative constant, \( K \), in Eq. 1 will be indicative of spatial patterns of erosion intensity during valley network formation. Finally, we hope to integrate our hydrologic modeling with simulations of early Martian climate to compare our estimates of regional variation in hydrologic conditions with predicted patterns of precipitation.

Conclusion: Both the breached basin analysis and the incision depth analysis for Isidis region suggest that a relatively humid climate characterized the brief period in Martian history during which valley networks formed.