GROUNDWATER AND FLUVIAL EROSION ON MARS: RECHARGE OR DEWATERING?

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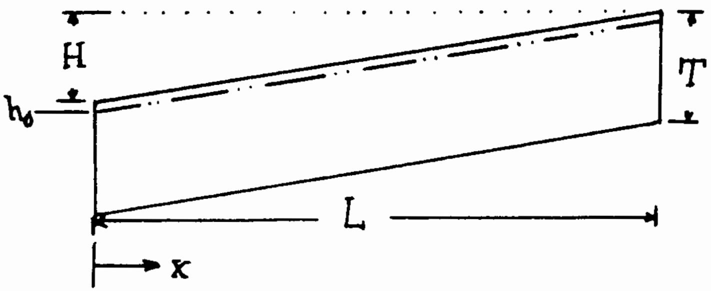
A wide variety of landforms on Mars have been attributed to the action of processes related directly or indirectly to the presence of groundwater or permafrost (1,2), including the widespread occurrence of channels of probable fluvial origin (3,4,5). However, a considerable range of uncertainty exists about the environment prevailing on Mars during formation of the fluvial channels and about the available quantity of water or ice (1,2,6).

Most current models of fluvial erosion on Mars invoke groundwater or ground ice as a reservoir and source of water. However, with the exception of (7) and (9), little attention has been directed towards groundwater flow mechanics on Mars. Preliminary simulations of two simple transient groundwater flow models have been made to assess the timescales of groundwater flow on Mars and the recharge rates that would be necessary to maintain active groundwater flow early in Mars' history. The models are cross-sectional models assuming shallow flow in a sloping aquifer. Flow is assumed to obey the Dupuit-Forchheimer assumptions for unconfined flow. In one model the horizontal permeability, k, and the porosity, η, are assumed to be uniform areally and constant with depth. The areally constant aquifer thickness is T, the length is L, and the surface elevation change over the length of the aquifer is H:



The initial conditions are that the aquifer is initially filled with water to within 100 m of the surface. The simulation is conducted with the outlet level of the water, h_0, at $x=0$ assumed to remain constant, and the water drains laterally through this face. The upstream face at $x=L$ is assumed to be a groundwater divide (no-flow). The proportion of the total water volume in the aquifer that is above h_0 (and therefore can flow out of the simulated section) is ϵ. Simulations have shown that the time, t_δ, required for δ percent of the available groundwater to flow out of the aquifer is given by:

$$t_\delta = T_\delta L^2 \nu \eta \epsilon / (kgH) .$$

Note that the times do not depend explicitly upon the aquifer thickness, T. The discharge per unit width, q, through the lower face of the aquifer is given by:

$$q_\delta = Q_\delta kgHT/(\nu L) ,$$

where g is the gravitational constant and ν the water viscosity. The following table (linear case) shows values of Q_δ and T_δ for several values of δ when H and L are measured in km, k in darcies, and t in years (for martian gravity and water just above freezing).

A similar set of simulations was conducted with the assumption that the permeability and porosity decrease exponentially with depth, h_S-h, beneath the surface, h_S:

$$\eta = \eta_0 \, e^{-\beta(h_S-h)} \text{ and } k = k_0 \, e^{-\beta(h_S-h)} .$$

The timescale, t_δ, can be expressed by an equivalent formula to that for the linear case if k_0 and η_0 are used. The appropriate formula for discharge estimation is:

$$q_\delta = Q_\delta k_0 e^{-\beta(h_s - h_w)} gHT/(\beta\nu L)\,,$$

where h_w is the outlet water surface elevation. Simulation results (Exponential) are shown in the table.

δ	Linear		Exponential	
	T_δ	Q_δ	T_δ	Q_δ
10%	0.14	1.0	0.13	1.0
50%	0.84	0.74	0.76	0.74
75%	1.73	0.32	1.46	0.37
90%	3.00	0.14	2.12	0.14

Timescales of Aquifer Dewatering: A representative scenario for martian global flow would have $L \approx 3000$ km, $H \approx 5$ km, $T \approx 10$ km, and $\eta \approx 0.1$. For these conditions, the timescale for 75% dewatering of the aquifer via lateral flow is ~10^6 years for permeability of 1 darcy, 1,000 years for 10^3 darcies (Carr's **(7)** assumed permeability for the martian regolith), and 10^9 years for 10^{-3} darcies. These results apply both to the homogeneous aquifer and to porosity and permeability decreasing exponentially with depth. MacKinnon and Tanaka **(9)** propose another model with a 1-2 km thick ejecta with permeability ~ 0.01 darcies and porosity ~0.15 overlying a 10 km fractured basement with permeability ~10^3 darcies and porosity ~0.01. Under these two-layer conditions, the effective relaxation timescale of the aquifer will be the maximum of the timescale for lateral drainage of the aquifer through the lower high permeability basement and the timescale for vertical drainage of the ejecta layer. If the basement aquifer is not completely confined then the effective time scale will be hundreds of years. However, since the porosity of the basement is so low, filling of the fractures in the bedrock by calcite, other mineralization, or weathering products **(10)** might effectively seal this layer and increase timescales for dewatering to 10^8 or 10^9 years.

Implications for Valley Network Development: There are several possible sources and release mechanisms for water forming valley networks:

1) *Sapping with groundwater recharge:* It is instructive to calculate the amount of recharge that would be required to maintain near-saturated conditions in the aquifer considered above. For 1 darcy permeability the recharge would be ~0.04 cm/yr, ~4×10^{-5} cm/yr for 10^{-3} darcies, and 40 cm/yr for 10^3 darcies. Thus the possibility of widespread groundwater seepage in an unconfined martian groundwater system depends critically on the regolith permeability. If it is high the groundwater table will be very low, and seepage will occur only at the lowest elevations on the planet (assuming recharge <1 cm/yr). If it is low (<1 darcy), groundwater levels will be high and seepage widespread but in small volumes. Modest groundwater-fed flow in the valley networks with ~5-20 km spacing between valleys would require recharge rates of 1 to 100 cm/yr.

2) *Erosion by runoff:* This is the typical terrestrial situation and requires either occasional intense rains (sufficient that precipitation rates exceed infiltration capacity) or seasonal melting of water-rich "snows" **(11)**. Either scenario requires an atmosphere considerably denser than at present and abundant water; whether such conditions ever occurred is a topic of considerable debate. Runoff would be encouraged by sufficient surface weathering to form near-surface clay or caliche horizons to retard infiltration. A shallow permafrost would also encourage runoff.

3) *Development from hydrothermal waters:* Under this scenario the formation of valley networks is suggested to be due to groundwater sapping resulting from local releases of melted permafrost by volcanic intrusions **(12,13)** or impact-generated heat **(14,15)**. Some of the collapsed terrains are likewise suggested to be due to lava intrusions as sills **(16)**. These processes can operate under atmospheric pressures and surface temperatures similar to those at present. However, a number of concerns may be raised. Mechanisms for incorporation of volatiles into the surface ejecta have not been elaborated. If the near-surface ejecta were ever unfrozen over large areas for a few thousand years much of the water would have been drained from the martian highlands if permeability is as high as **(7)** and **(9)** assume. Early in Mars' history permafrost would be thin due to high thermal gradients. Terrestrial hydrothermal systems generally involve meteoric water circulating under groundwater gradients developed by recharge. Therefore, in the absence of recharge by some such mechanism as

vapor phase transport (8), only regolith water above the level of surface seeps would be available for mobilization. Such mechanisms might be adequate for development of channel systems on the lower flanks of volcanic shields and valleys such as Nirgal Valles, which heads in a large undissected upland. However, the Noachian valley systems have much smaller contributing areas and the channels often extend almost to crater rims. Erosion of channels by runoff or seepage probably requires volumes of water 10^2 to 10^5 times the volume of eroded solids (17); furthermore, the extent and depth of fluvial dissection in the cratered terrain may be greater than previously estimated (18).

In summary, erosion of valley networks by runoff or sapping with surface recharge seem most consistent with hydrological considerations. Atmospheric conditions conducive to recharge need not have lasted long ($\sim 10^6$ to 10^7 years in total) and could have been episodic depending upon impact and volcanic history (19,20).

Implications for Outflow Channel Development: The distinctive characteristic of the outflow channels is the need for rapid mobilization of large quantities of water and debris. Supply of water from hydrothermal melting of permafrost is common to many of these models. Again, a number of possible release mechanisms have been proposed:

1) *Release from confined aquifers:* In this scenario water is confined by permafrost (7) or a relatively impermeable ejecta regolith (9). Sudden release of water is due to aquifer pressures exceeding the overburden weight. Permeability must be very high ($\sim 10^3$ darcies) to release sufficient water, and the confining permafrost or ejecta must be monolithic to prevent slower dewatering. Otherwise very rapid hydrothermal melting would be required over time periods $< 10^3$ years to counterbalance lateral drainage. As discussed above, the retaining of large volumes of groundwater in high permeability aquifers well above global baselevel is problematic. It has been suggested that occurrence of massive debris flow might relieve the large discharge requirement (9).

2) *Release from surface storage:* One-time or episodic breaching of tectonic, thermokarstic, or ice-dammed depressions (e.g. Valles Marineris and chaotic terrain) via surface or subsurface drainageways is another possibility. Some outflow valleys are not obviously connected to an appropriate surface reservoir except by putative subterranean routes. This mechanism has the advantage of not requiring sudden mobilization of groundwater. This might be an effective mechanism if combined with recharge from melting of southern latitude ice deposits (21,22).

3) *Tectonic uplift:* Direct aquifer pressuring due to land uplift and tilting could only occur if the aquifer were either very impermeable or tightly confined both vertically and laterally, due to the slowness of tectonic deformation.

4) *Tectonic fracturing:* Large fractures would serve as very effective conduits for groundwater flow (9,23). If these intersected surface storage or confined aquifers then rapid outflows could occur. If the original basement rock were initially impermeable, then new fractures could provide rapid drainage of the overlying ejecta zone due to the reduction in effective length scales.

In summary, the major difficulty with a direct groundwater source for large floods in outflow channels is providing large reservoirs of groundwater in aquifers of high permeability while maintaining artesian aquifer pressures.

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