Planetary Scale Groundwater and Surface Water Interaction on Early Mars. E. Hiatt[1,3,4,*], M. A. Shadab[2,3,†], and M. A. Hesse[1,2,3,‡]. [1]Department of Geological Studies, Jackson School of Geosciences, [2]Oden Institute for Computational Engineering and Sciences, [3]Center for Planetary Systems Habitability, [4]Institute for Geophysics, The University of Texas at Austin, Austin TX ([*]eric.hiatt@utexas.edu, [†]mashadab@utexas.edu, [‡]mhesse@jsg.utexas.edu).

Introduction: There is ample evidence for an active hydrologic cycle early in the Martian past [e.g. 1,2]. In the oldest terrains, incised valley networks retain the record of erosional events capable of large-scale denudation [e.g. 3,4]. Light layered deposits located in Arabia Terra are inferred to be evaporite deposits formed by a fluctuating water table cyclically breaching topography [5]. The duration, intensity, and frequency of these processes remain unconstrained.

Previous groundwater modeling has attempted to constrain groundwater fluctuation at Arabia Terra but lacked the ability to form standing bodies of water [6,7]. However, on a first order, steady state basis, we have shown that the model's inability to pond water is inconsequential. Groundwater to surface water interaction is a secondary control when compared to the mean aquifer recharge rate and hydraulic conductivity [8].

To accurately model a transient Martian groundwater system that can interact with surface bodies of water, the coupling between the aquifer and water body must be accounted for (see Figure 1). If a northern ocean once existed in the Martian lowlands as some suggest [e.g. 1,2], mass conservation requires that an increases in the groundwater table elevation must be accompanied by decreased water volume in the ocean and subsequently a lower shoreline. Conversely, if the highland aquifer were to cease receiving recharge, shoreline elevation must increase as groundwater table elevation recedes.

The coupling between groundwater and surface water bodies becomes consequential when numerically modeling due to the need to prescribe a boundary condition at the shoreline. This boundary allows our model to deactivate computational cells assuming an equipotential surface across the open body of water. This is difficult because the coupling seen in Figure 1 requires a dynamic, non-linear Dirichlet boundary. Understanding the transient aquifer response and placing constraints on climatic excursions producing conditions favorable to recharge requires a method to accurately calculate the dynamic coupling between the putative northern ocean and the southern highlands aquifer. Here, we present a framework for properly parameterizing boundary conditions at this interface to facilitate parameterizations of future transient numeric models.

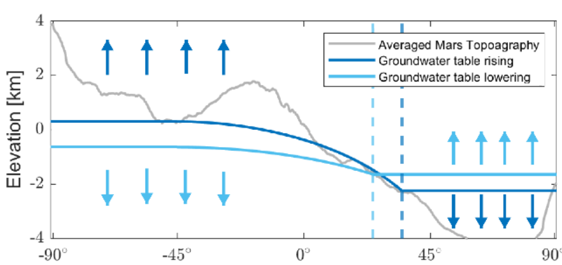

Figure 1- Cross sectional view of the Martian crust from south to north pole with longitudinally averaged topography in grey. Rising and lowering water tables are depicted to illustrate the connection between a putative northern ocean and the groundwater table.

Method: Similar to other groundwater studies [e.g. 6,7], we use the steady-state, non-linear equation for an unconfined aquifer called the Dupuit-Boussinesq approximation for the height, h, of the groundwater table above the base of the aquifer, at -9 km on datum, where h is known as the hydraulic head level. The aquifer has length, l, and the basin has width, w. As boundary conditions, we have a symmetry condition at the south pole producing a no-flow boundary and at the interface between the aquifer and shoreline we set the hydraulic head to $h(1)= h_o$. Aquifer porosity, ϕ, and hydraulic conductivity, K, are constant.

With the assumption that the cumulative water volume between of aquifer, V_g, and ocean, V_o, remains constant, we can assume the constraint $V_{g\,+}\,V_o = V$, where V is the total water volume in the system. After non-dimensionalizing the governing equation and introducing internal length scales, we have:

$$Pr = \frac{h_p}{h_o} = \frac{q_p l^2(\phi l + w)}{KV} \geq 0$$

where q_p is the flux term associated with aquifer recharge and P_r is a non-dimentional term that can be interpreted as the change in h due to recharge relative when compared to the mean water level. This occurs when the ocean and groundwater are equal elevation. After substituting Pr and non-dimensional parameters into the boundary condition at the interface, a non-dimensional formulation for the head level at the interface and a non-dimensional capacity number become:

$$h_o = \Pi = 1 + \frac{1}{Ca}\left(1 - \int_0^1 h\, dx\right)$$

and

$$Ca = \frac{w}{\phi l}$$

To couple the shape of the groundwater table with the head level at the interface, we assume mass balance and have:

$$H\left(\Pi, Pr\right) = \frac{\sqrt{Pr}\left(Pr + \Pi^2\right)\arcsin\sqrt{\frac{Pr}{(Pr+\Pi^2}} + \Pi Pr}{2Pr}$$

where H is the constrained function for the head at the boundary. Knowing that Pr must be greater than or equal to zero, we can examine plausible values of the hydraulic head at the interface given recharge rate and aquifer parameters.

Results: The derived equations allow us to examine the parameter spaces associated with Ca, Pr, and Π. For $Pr > 0$ only solutions with $H > 1$ are possible, because the groundwater volume must increase with precipitation over the mean water level. As such we can identify feasible and infeasible regions in parameter space. The infeasible region lies below the red line seen in Figure 2.

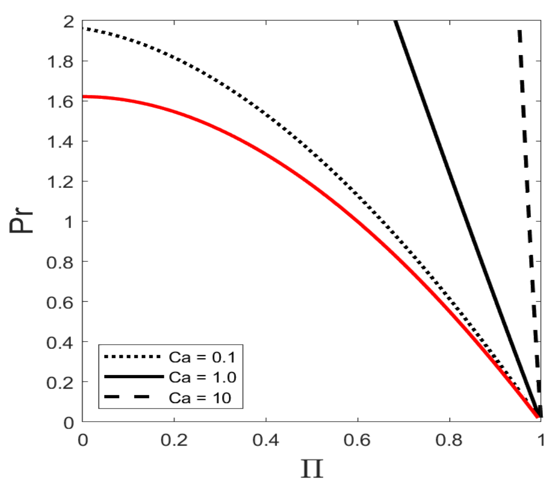

Figure 2- Plot of parameter space between Pr and Π with varied values for Ca. The area beneath the red line are infeasible values given the previously specified constraints.

For illustrative purposes, we will use a capacity number, $Ca = 1$, and examine the effects of head level elevation at the ocean-aquifer interface on the shape of the groundwater table under the assumption of uniform distribution of recharge across the domain. Results can be seen in Figure 3. The parameters used are all non-dimensional and this analysis can be extended to any value chosen for Ca, which is a function of the width of the ocean at a given latitude divided by the porosity scaled by the length of the aquifer.

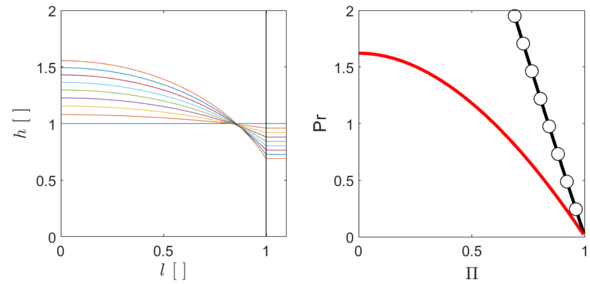

Figure 3- In the left panel, a parameter sweep of hydraulic head level at the interface versus aquifer and ocean hydraulic head elevations. The right-hand panel displays the plot of Ca in Pr and Π parameter space with solutions represented as circles on the black line.

Discussion: We have presented a mass balance framework for solving a non-linear boundary condition for the steady-state, non-linear Dupuit-Boussinesq approximation. This formulation will be necessary when the model is extended to transient cases. Previous work leveraged geomorphic observations to constrain plausible recharge rates on the southern highlands aquifer on early Mars [8]. Using the same rational, future modeling work will allow constraining the time scales associated with the climactic fluctuations thought produced conditions favorable for aquifer recharge.

It is of interest to note that the fluctuating groundwater table elevation given a chosen head elevation at the interface qualitatively corresponds to the location of the evaporite deposits seen in Arabia Terra. Further investigation will be required to examine the possibility that dynamic coupling between the southern highland's aquifer and the ocean forced by climactic oscillations could have produced the observed deposition.

References: [1] Carr, Michael H. "The fluvial history of Mars." *Philosophical Transactions of the Royal Society A: Mathematical*, Physical and Engineering Sciences 370.1966 (2012): 2193-2215. Author A. B. and Author C. D. (1997) JGR, 90, 1151–1154. [2] Carr, Michael H., and James W. Head III. "Geologic history of Mars." Earth and Planetary Science Letters 294.3-4 (2010): 185-203. [3] Baker, Victor R., et al. "Channels and valley networks." Journal of Environmental Sciences (China) English Ed (1992): 493-522.[4] Hynek, Brian M., Michael Beach, and Monica RT Hoke. "Updated global map of Martian valley networks and implications for climate and hydrologic processes." Journal of Geophysical Research: Planets 115.E9 (2010). [5] Andrews-Hanna, Jeffrey C., Roger J. Phillips, and Maria T. Zuber. "Meridiani Planum and the global hydrology of Mars." Nature 446.7132 (2007): 163-166. [6] Andrews-Hanna, Jeffrey C., et al. "Early Mars hydrology: Meridiani playa deposits and the sedimentary record of Arabia Terra." Journal of Geophysical Research: Planets 115.E6 (2010). [7] Andrews-Hanna, Jeffrey C., and Kevin W. Lewis. "Early Mars hydrology: 2. Hydrological evolution in the Noachian and Hesperian epochs." Journal of Geophysical Research: Planets 116.E2 (2011). [8] Hiatt, Eric, et al. "Limited Recharge of a Steady Deep Groundwater Aquifer in the Southern Highlands of Early Mars." Authorea Preprints (2022). [9] Bear, Jacob. Dynamics of fluids in porous media. Courier Corporation, 1988.