MODELING GROUNDWATER FLOW TO GALE IN A WARMING CLIMATE. Mark Baum[1] and Robin Wordsworth[1,2], [1]Department of Earth and Planetary Sciences, Harvard University (markbaum@g.harvard.edu), [2]School of Engineering and Applied Sciences, Harvard University (rwordsworth@seas.harvard.edu).

Introduction: Orbiter and rover data have revealed a long and complex hydrological history in Gale Crater, constraining the climate history of Mars [1]. At least three separate lake stands have been identified from satellite imagery of deltas and other features in the crater, thought to have formed between ~3.6 Ga and ~3.4 Ga [2]. These lakes were likely part of a sustained hydrological cycle and were sourced by an evolving balance of local surface water, regional surface water, and subsurface flow. Individual lake stands are thought to have formed over tens of thousands to hundreds of thousands of years. The intermittency, relatively brief persistence, and apparently sudden initiation/cessation of these lake sustaining periods appears compatible with a primarily cold climate punctuated by geologically brief periods of hydrological activity.

Groundwater flow to Gale Crater during lake-sustaining periods is not well constrained, but it may have been significant. As noted by many, Gale's deep crater floor and location directly at the base of the hemispheric dichotomy make it a likely destination for topographically driven groundwater. Modeling of integrated regional hydrology surrounding Gale in a steady, warm climate indicates that a semiarid scenario matches lake levels and that subsurface flow accounts for roughly 40 % of the water flux to Gale [3].

However, based on the observations, an unsteady climate with wide-ranging surface temperatures needs further exploration. Climate transience would impact all components of the hydrological cycle, but the groundwater response to changing climate is not well accounted for and the long timescales of groundwater flow and heat propagation through the crust could make the subsurface a relatively stable water source. Understanding this source is a crucial part of inferring past climates from ancient lake deposits at Gale.

Model: We model groundwater flow to Gale in a warming climate over a wide range of physical parameters. The model is as simple as possible while capturing the effect of the regional topography at Gale (Figure 1), depth dependent hydraulic properties, and a downward thawing aquifer. Specifically, the heat equation is solved in the vertical dimension, determining the depth of the freezing point (273 K in the model). The Boussinesq (vertically averaged) groundwater equation is solved in one horizontal dimension for the water table elevation, where the freezing point determines the bottom of the mobile groundwater zone and the surface is represented by idealized/averaged Gale topography.

Porosity and permeability decrease exponentially with depth in our model. Although the hydraulic properties of the Martian crust are not known, roughly exponential profiles are common in Earth's crust [4] and agree with seismic study of the Moon's near-surface [5]. Given the enormous uncertainty, we test a wide range of surface values and decay lengths for the exponential profiles. The temperature dependence of water's viscosity is included in the model. A range of thermal conductivities representative of water saturated basalt are used. The geothermal heat flux is set to 30 mW/m^2. This value is not well constrained but has very little bearing on the results.

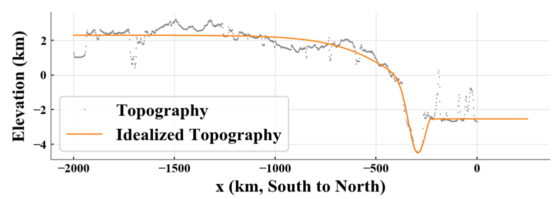

Figure 1: Idealized topography used for modeling. Grey dots show a cross-section of MOLA topography running north into Gale. The orange line shows model topography, generated by a series of fits.

Starting with a water-saturated crust, a cold surface temperature (220 K), and an equilibrium crustal temperature profile (a geotherm), the surface is rapidly warmed to 285 K over tens of years and the water table evolves over 5000 yr. As the freezing point propagates downward, the mobile thickness of the crustal aquifer increases, liberating an increasing section of the saturated zone for flow. Groundwater converging at the center of Gale pushes the water table to the surface. We assume all water breaching the surface is removed from the subsurface. In reality, upwelling groundwater may have pooled or fed an existing lake, but we mainly consider the early period of lake formation when lake levels are low enough not to significantly affect the hydraulic gradient. To establish a baseline set of results, recharge is zero throughout the model domain.

Results: First, we examine sensitivity to the principle physical parameters in the model. The permeability is, perhaps unsurprisingly, the dominant control on groundwater flow. However, the volume flux of water is mostly insensitive to surface porosity in the range 0.05 to 0.2. This is because the rate of water table rise is inversely proportional to porosity but the volume of water breaching the surface is proportional to it, so the surface porosity cancels. The decay lengths of the exponential permeability and porosity profiles have only very small impacts on the total water flux (Figure 2) because the freezing point migrates only 100-200 m below the surface after thousands of years. The modeled decay lengths are larger than 1 km, so the shallowest 200 m are similar in porosity and permeability.

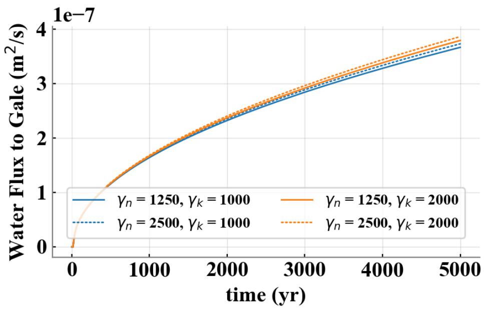

Figure 2: Water volume flux (area flux for 1D model) to Gale for a factor of 2 difference the exponential decay length of the porosity (γ_n) and the exponential decay length of the permeability (γ_k), holding all other parameters constant. These lengths have very little impact.

Next, we make an assessment of the time required to generate significant groundwater flow in a warming climate. Figure 4 shows the volume flux to Gale for a wide range of surface permeability values and a factor of 2 difference in the thermal conductivity. The highest permeability generates maximum flow in about 100 years, a climatically short interval. Lower permeability leads to a slower increase in the water flow, but the flow rate plateaus within one or two thousand years for the whole range, a meaningfully short timescale in the context of the estimated 10,000-100,000 year lake-sustaining periods. In all cases, thermal conductivity has only a marginal effect.

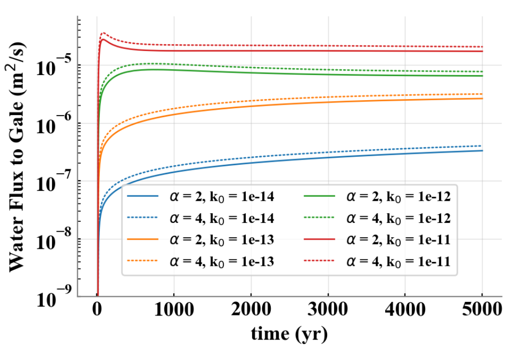

Figure 3: Water volume flux (area flux for 1D model) for a wide range of surface permeabilities (k_0) and a factor of 2 difference in thermal conductivity (α). All other parameters are held constant. The conductivity has a small effect, but the permeability dominates.

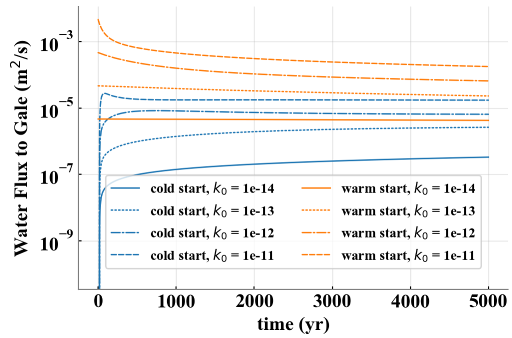

Figure 4: Water volume flux (area flux for 1D model) to Gale for a range of surface permeabilities (k_0) with a steady, warm crust and with a cold crust warmed rapidly at the surface. Warm starts began with a surface temperature of 285 K and cold starts with 220 K.

Finally, we compare the rapidly warming scenario to a steadily warm scenario where a full 8 km of the crust is available for flow. Figure 3 shows the volume flux to Gale for a range of permeabilities and cold/warm initial surface temperatures. As expected, the difference is greatest during the initial warming. After several thousand years, the difference between warm and cold starts is one or two orders of magnitude.

Further Work: These results demonstrate that permeability is unquestionably the dominant parameter, provide a rough timescale for groundwater flow to Gale in a warming climate, and begin comparing warming climates to steadily warm ones. However, the results must be considered in the context of lake stability. In particular, we will assess the circumstances under which these volume fluxes could be a meaningful fraction of lake water influx for a range of evaporation rates, surface water fluxes, and recharge rates.

References: [1] J. P. Grotzinger et al. (2015) *Science, 350*. [2] M. C. Palucis et al. (2016) *JGR*, *121*, 472-496. [3] D. G. Horvath and J. C. Andrews-Hanna (2017) *GRL, 44*, 8196-8204. [4] D. Demming (1954) *Introduction to Hydrogeology*. [5] S. M. Clifford (1993) *JGR, 98*, 10973-11016.