Question 1. Here we’re going to investigate Martian gullies.

a) Let’s say the grain size is 10cm. What is the critical friction velocity? Take \( g = 3.7 \, \text{m/s}^2 \), \( \theta = 0.1 \), \( \rho_s = 3000 \, \text{kgm}^{-3} \) and \( \rho_f = 1000 \, \text{kgm}^{-3} \). [1]

b) The slopes are about 20°. What is the minimum flow depth required to cause sediment to move? Is sediment transport likely to happen? [2]

c) Let’s take a wild guess and assume that \( h = 1 \text{m} \) when the gullies were flowing. Calculate the rates of sediment discharge and water discharge \((\text{in m}^2 \, \text{s}^{-1})\) assuming that both friction factors are 0.05. [2]

d) What is the ratio of sediment:water transported? [1]

e) The depositional apron has a volume of \( 10^7 \, \text{m}^3 \). Assuming that the channel width is ten times \( h \), how long would it have taken the apron to form under steady-state conditions? [2]

f) What volume of water was discharged? [1]

g) Let’s assume that this water was initially locked up in an aquifer of dimensions \( L \times T \times d \) and porosity \( \phi \) (see Figure). Taking \( T = 100 \text{m} \), \( d = 1 \text{km} \) and \( \phi = 10\% \), what is the value of \( L \)? [1]

h) Once the aquifer was breached and started draining, the disturbance to the water table will have propagated inwards (see Figure). If the duration of the gully flow is set by this propagation timescale, what is the hydraulic diffusivity of the aquifer? [2]
i) What is the corresponding permeability? You can take the pressure drop to be $\rho_f g T$ and the viscosity of water to be $10^{-3}$ Pa s. [1]

j) What is the implied grain size in the aquifer? Does that seem reasonable? [2]

k) Discuss in qualitative terms how your estimates of discharge rates, sediment:water ratio, formation timescale and permeability would change if you had assumed a smaller channel depth $h$. [4] [19]

**Question 2.** Also Mars, but here we will examine (much) larger features.

a) Sediment transport will increase channel depth $h$. The rate of channel downcutting $dh/dt$ can be approximated by $q_s/L$, where $q_s$ is the sediment discharge rate ($m^2 s^{-1}$) and $L$ is a lengthscale (constant) over which the slope of the channel changes.

Write down an expression for $dh/dt$ in terms of $h$, $L$, $f_s$, $\alpha$, $g$, $\rho_s$ and $\rho_f$. [1]

b) Hence find an expression for how $h$ varies as a function of $t$. Your boundary condition is that $h=h_0$ at $t=0$. [3]

c) Using your answer to b), find an expression for the time it takes for the channel depth to double (from $h_0$ to $2h_0$). [2]

d) How does your answer to c) change if you change the friction coefficient or the slope? Do these answers make physical sense? [2]

e) A recent Martian outflow channel has $h=50m$, a width of 1km and it descends 200m in elevation over 100 km distance. For this channel depth, what is the total water discharge rate (in m$^3$/s)? You may take $f_s=f_w=0.05$ and $g=3.7$ ms$^{-2}$. [1]

f) Using your answer to c), how long did it take for the channel depth to double (from 25m to 50m)? Take $L=100$ km, $\rho_s=3000$ kgm$^{-3}$ and $\rho_f=1000$ kgm$^{-3}$. [1]

g) Roughly what was the total volume of water discharged during this time (in km$^3$)? [1]

h) How does that volume compare with the volume stored in Lake Tahoe? [1] [12 total]

**Question 3 (bonus/grads)**

a) Given the expression for water discharge rate in your notes, write down an expression for the mean velocity $u$ of the water (m/s) [1]

b) Hence write down an expression for $u/u^*$ in terms of $h, d, \alpha, \theta$, a friction coefficient and densities. [2]
c) For the worked Titan example in your notes, how much larger is \( u \) than \( u^* \)? (You can check your answer against the Burr et al. 2006 diagram). [2]

d) The meanders on Venus presumably require turbulent flow to form. Turbulence implies that the Reynolds number \( Re > 1000 \), where \( Re = h u \rho / \eta \). Using your answer from a), write down an expression which gives an upper bound on the viscosity \( \eta \) in terms of \( h, g, \alpha, \rho \) and a friction coefficient. [2]

e) Let’s take \( h = 10 \) m, \( \sin \alpha = 0.001 \), \( \rho = 3000 \) kg m\(^{-3}\) and \( g = 9 \) ms\(^{-2}\). What is the maximum possible viscosity of the Venus lavas? You may take \( f_w = 0.05 \). [2]

f) How long would it take this flow to travel 1000 km? [2]

g) How does your answer to f) compare with the conductive cooling timescale of the lava? (Take \( \kappa = 10^{-6} \) m\(^2\)s\(^{-1}\)). Do you think that conductive cooling is the way that this lava flow loses heat? [3] [14 total]