2020 ESS 132: Terrestrial Hydrology Homework 3

You are welcome to work together on this homework to understand the concepts but your answers must be in your own words. Group answers are not acceptable. Please show your workings wherever relevant. Your completed homework is due by 11.59p.m. on Friday 11/20 (Week 7).

Part A: Concepts and calculations related to soils and infiltration (25)

1. Characterizing soils (6)

A soil sample has a volume of 100 cm^3 and a weight of 176g. After drying the sample in an oven at 105 ^oC for a day, the weight was reduced to 164g. The soil was then completely saturated with water resulting in a weight of 218g. Finally, the sample was drained (removal of gravity water) and the weight was determined as 188g.

Calculate the:

a) gravimetric water content at the beginning (1)

$\theta_g = M_w / M_s$ where M_w = mass of water, M_s = dry weight of soil

initial soil mass = 176 g

M_s = 164 g

M_w = initial soil mass – dry soil mass = 176 g – 164 g = 12 g

θg= Mw/ Ms = 12g/164g = ***0.0732***

b) porosity (Hint – the density of water = 1 g/cm^3. Remember that saturated soil contains no air.) (2)

saturated soil mass = 218 g

saturated water mass = saturated soil mass – dry soil mass = 218 – 164 = 54 g

$$saturated\ water\ volume\ (total\ pore\ space) = 54\ g \times \frac{1\ cm^3\ water}{1\ g\ water} = 54\ cm^3$$

soil volume = 100 cm^3

$$porosity = \frac{total\ pore\ space}{soil\ volume} = \frac{54\ cm^3}{100\ cm^3} = \mathbf{0.54}$$

c) the field capacity of the soil in cm^3/cm^3 (2)

soil field capacity mass = 188 g

field capacity water mass = soil field capacity mass – dry soil mass = 188 g – 176 g = 24 g

$$field\ capacity\ water\ volume = 24\ g \times \frac{1\ cm^3}{1\ g} = 24\ cm^3$$

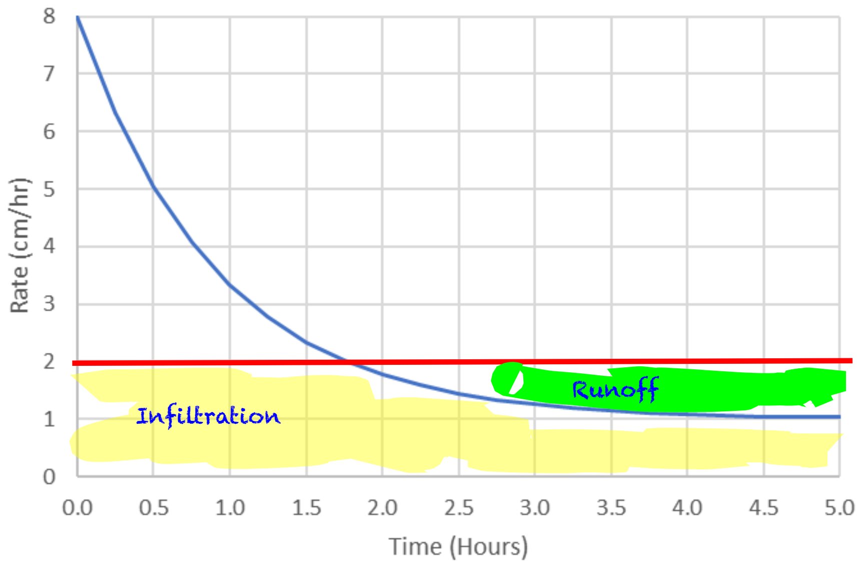
$$field\ capacity = \frac{field\ capacity\ water\ volume}{soil\ volume} = \frac{24\ cm^3}{100\ cm^3} = \mathbf{0.24\ cm^3/cm^3}$$

d) If the permanent wilting point of this soil is 0.04 cm^3/cm^3, what is the "available water" which could be used by plants? (1)

Available water = field capacity – permanent wilting point = 0.24 cm^3/cm^3 - 0.04 cm^3/cm^3

= ***0.20 cm^3/cm^3***

2. Consider a soil characterized by the infiltration capacity curve shown on the graph below. This is an example of the **Horton method** of characterizing infiltration. (8)



The infiltration capacity curve shown is an empirical relationship which seems to match well with observations for this watershed: $f_t = 1 + (8-1)\ e^{-1.1t}$

a) Use your notes from Lecture 12a to work out what the terms represent in the above equation: (1)

Initial infiltration capacity at time 0 (f_0) = ***8*** cm/hr

Infiltration rate of saturated soil (f_c) = ***1*** cm/hr

Decay constant for this particular soil (k) = ***1.1*** hr^{-1}

b) A 4 hour storm occurs with rainfall rates of 2cm/hr.

i. What is the total depth of rain that would fall? (1) 2 cm/hr * 4hr = ***8*** cm

ii. On the graph, shade the area of the graph which represents how much infiltration would occur and also highlight the area of the graph which represents how much runoff would occur. (2)

iii. Use the graph to make very rough estimates for how much water will infiltrate and how much water will run off. (Tip – how much water does each square on the graph represent?) (2)

Amount of infiltration = ***7*** cm Amount of runoff = ***2*** cm

iv. On the graph label the time when runoff would start to occur (i.e. when ponding starts). (1)

v. If the drainage basin is 300,000 m^2, what volume of runoff occurs due to this storm? (1)

$$f = f_c + (f_0 - f_c)e^{-kt}$$

Rearranging the equation to solve for the time when rainfall rate = infiltration capacity

$$t = \frac{\ln\left(\frac{f - f_c}{f_0 - f_c}\right)}{-k} = \frac{\ln\left(\frac{2-1}{8-1}\right)}{-1.1} = 1.769\ hr$$

Assuming that the infiltration rate = infiltration capacity, I took the definite integral of the Horton equation to calculate the amount infiltrated between 2 timepoint and arrived at the following equation:

$$F_{t_1}^{t_2} = f_c t_2 - f_c t_1 + \frac{(f_0 - f_c)(e^{-kt_2} - e^{-kt_1})}{-k}$$

The total amount of rainfall after rainfall rate = infiltration capacity is:

$$rainfall = 2\frac{cm}{hr} \times (4\ hr - 1.769\ hr) = 4.462\ cm$$

The total amount that had infiltrated after rainfall rate = infiltration capacity is:

$$F_{1.769\ hr}^{4\ hr} = \left(1\frac{cm}{hr} \times 4\ hr\right) - \left(1\frac{cm}{hr} \times 1.769\ hr\right) + \frac{\left(8\frac{cm}{hr} - 1\frac{cm}{hr}\right)\left(e^{-1.1\times 4\ hr} - e^{-1.1\times 1.769\ hr}\right)}{-1.1\ hr^{-1}}$$
$$= 3.062\ cm$$

The runoff height is:

$$runoff\ height = rainfall - F_{1.769\ hr}^{4\ hr} = 1.400\ cm$$

The runoff volume is:

$$300{,}000\ m^2 \times 1.400\ cm \times \frac{1\ m}{100\ cm} = 4200\ m^3$$

Volume = 4200 m^3

3. Green-Ampt model of infiltration (11)

This model can be used to answer many important questions that hydrologists and water managers have whenever rain falls. What will the total runoff and infiltration be? When will runoff begin? How will infiltration rates vary throughout the storm?

A storm lasts for 4 hours with a rainfall rate of 0.7cm/hr. The soil's K_{sat} (or K_s) = 0.032 cm/hr, ψ_f = 20.8cm, θ_i = 0.15 and θ_s = 0.5 .

a) To determine the amount of infiltration from the storm you will first have to work out the time at which ponding occurs (t_p). To do this you also have to work out the amount of water you can add to the soil before ponding occurs (F_p). Calculate these using the formulae from class. (2)

$$F_p = \frac{|20.8\ cm| \times 0.032\frac{cm}{hr} * (0.5 - 0.15)}{0.7\frac{cm}{hr} - 0.032\frac{cm}{hr}} = 0.3487\ cm$$

$$t_p = \frac{0.3487\ cm}{0.7\ cm/hr} = 0.4982\ hr$$

F_p = 0.3487 cm

t_p = 0.4982 hr

b) The next part of the problem involves selecting the appropriate formulae for different values of F and using trial and error to discover the related time (t) and infiltration rate (f) for the end of the storm. This also allows you to see how the behavior of the soil changes over the duration of the storm. See Lecture 12b for an example of this. You will find this easier and quicker to do in excel!

Answer the related questions below: (5)

What is the total amount of rainfall for this storm? 2.8 cm

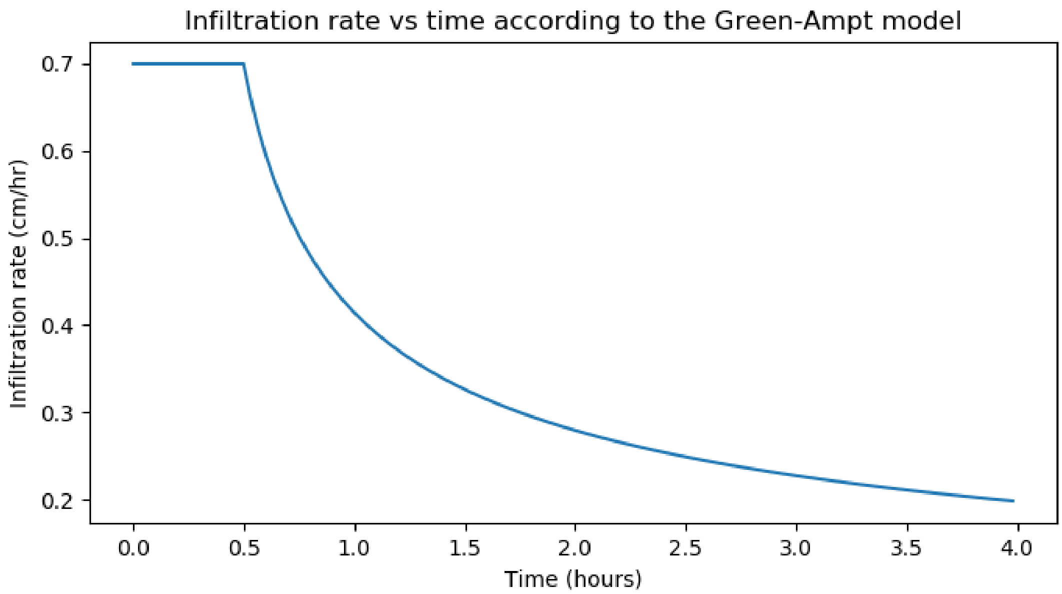
What is the value of F at the end of the storm? 1.4 cm

What is therefore the amount of runoff as a result of this storm? 1.4 cm

What is the infiltration rate at the beginning of the storm? 0.7 cm/hr

What is the infiltration rate at the end of the storm? 0.1984 cm/hr

Copy/paste a graph below of the infiltration rate vs time for this soil and storm. (4)



Part B: Infiltration and groundwater recharge from the surface (9)

Rather than focusing on above-ground projects such as the big aqueducts and dams, recently attention has turned to the potential value of promoting groundwater replenishment by infiltration from the surface. Here in Orange County we already benefit from this system. This is a good introduction to some of the concepts and issues we will think about in the coming weeks.

http://waterinthewest.stanford.edu/groundwater/recharge/

a) Explain at least 4 benefits of using groundwater recharge to increase California's water resources rather than dams or seawater desalination. (2)

   1. It generally costs less than either expanding surface water storage or desalination; there are lower costs from construction and permitting, and it also uses less energy than desalination and so has reduced energy costs compared to desalination.
   2. Evaporative water loss is negligent as opposed to surface reservoirs, allowing for high amounts of storage.

3. Because of reduced energy use compared to both reservoirs and desalination, groundwater recharge releases much less greenhouse gases than surface water storage methods and desalination.
4. California's aquifers are estimated to hold 17-26 times as much water as surface reservoirs. If groundwater recharge is properly utilized, it will allow California to hold huge amounts of water.

b) How does the storage capacity of groundwater basins compare to the capacity of dams in California? (2)

The storage capacity of California's groundwater basins dwarf that of dams: California groundwater basins can store 850 million-1.3 billion acre-feet, while California dams hold less than 50 million acre-feet.

c) Explain the 4 considerations we have to consider when proposing and planning for artificial recharge projects. Based on what we learned about infiltration, what sort of soil/sediment would be best. (3)

1. The type of soil and underlying material of an aquifer is a key consideration. Grain sizes must be fairly large and uniform so that the aquifer and the layers of material above it is permeable. This ties into the following consideration:
2. Land. There must be land that is suitable for recharge (i.e. have the suitable underlying soil and geology), and the amount of land available for recharge will also shape the choice of recharge (either by taking up large amounts of land for recharge ponds that allow water to infiltrate naturally or by using up smaller amounts of land for injection wells that forcefully pump water downwards).
3. Sources of water are another consideration. Sources of water must exist first before recharge can occur. In addition, some sources of water cannot be used for recharge, and if they are the only sources that a community can access, then the community cannot perform groundwater recharge. Certain acceptable sources of water still require treatment before the water from that source can be used to recharge groundwater. For example, stormwater runoff carries pollution from vehicle exhaust and trash.
4. Water must be transported to the recharge site itself. Engineers and watershed managers need to decide whether to use natural artificial means and must engineer methods of transporting water accordingly.

A soil that consists mainly of well-sorted sand probably would work best. The large grain size of sand allows water to seep in relatively quickly, and the well-sorted nature of the material would mean that there are few to no small particles that can block gaps between sand particles, allowing for unimpeded infiltration into the soil.

d) Why would it be difficult to expand the use of recharge ponds in urban areas? (2)

Because infiltration is a rather slow process, recharging significant amounts of water require significant amounts of land to allow water to seep through. Urban areas don't have much land available, and any available land would likely to be expensive, potentially driving up initial costs of establishing recharge ponds.

Part B: Groundwater use and sustainability in the US (16)

Currently we are not using groundwater sustainably in a lot of locations around the world and this has the potential to become a huge problem. The paper this week explores groundwater depletion and sustainability of irrigation in the Central Valley of California and the US High Plains. Figure 1 in the paper has a nice map to show the region we call the High Plains for those of you (like me) who were unfamiliar with it.

http://www.pnas.org/content/109/24/9320.abstract

a) According to the abstract what % of irrigation in the US relies on groundwater? (1)

60% of irrigation in the U.S. relies on groundwater.

b) How old do scientists think the groundwater may be in the southern High Plains aquifer? Why should this concern us? (2)

The water in the southern High Plains aquifer was recharged mostly 13,000 years ago. This means that the recharge of this aquifer is a very slow process, and that the aquifer is not being recharged at a rate that is on par with withdrawal. If the groundwater continues to be improperly managed, this can result in a severe lack of water that can endanger agriculture and the economic productivity of the region.

c) What has groundwater extraction done to rivers and streams in the High Plains region? (2)

Streamflow in rivers and streams in the region have decreased due to reduced discharge (base flow) to these streams. Base flow was reduced by up to 50% in some cases.

d) Current laws do restrict how much water can be extracted in Central Valley. What are the laws designed to prevent happening? (2)

The Groundwater Management Act of 2014 requires Groundwater Sustainability Agencies be formed for medium to high priority groundwater basins all throughout the state. The Act also requires that sustainable management plans be formed for these basins so that groundwater can be used sustainably without drawing up more than can be recharged.

e) What are the projected lifespans of the High Valley aquifer and Central Valley aquifer? What factors might cause those estimates to change significantly? (2)

Projected lifespans are fairly variable in the High Plains aquifer. In the north where recharge is plentiful, there are no depletions and so the projected lifespan might as well be infinite. Projected lifespans in the Kansas region of the central High Plains aquifer are 240 years, but there is even more variability within the Kansas region itself as a significant portion of the depletion occurs over a very small area. This variation in projected lifespan can be explained by variations in recharge. The northern High Plains see very high recharge compared to the central and southern High Plains, resulting in long lifespans in the north but lower lifespans in the central and south High Plains.

Projected lifespans in the Central Valley aquifer are also fairly variable, with the northern part of the aquifer (Sacramento groundwater basin) seeing no depletion while most of the depletion is in the Tulare basin towards the south. Precipitation partially explains this variation, as depletion is the highest in the Tulare basin where precipitation is at its lowest in the Central Valley. The aquifer as a whole also sees more temporal variation in groundwater storage. This temporal variation also coincides with precipitation. The aquifer see steep declines during droughts while they also experience partial recoveries in normal years with no drought.

f) One of the suggested approaches to reduce water demand in the Central Valley is to move towards more efficient “sprinkle” irrigation systems. Why might this not actually result in real water savings? (2)

Several studies argue that runoff from excessive irrigation actually serves as a form of recharge, and by switching to “sprinkle” irrigation systems that limit water use, farmers will produce less runoff and will reduce recharge for the Central Valley, which can cause further depletion of the aquifer.

g) What are some of the problems of converting from irrigated crops to rainfed crops in the High Plains? (2)

This can reduce crop yields by 2-2.5 times and produce other economic impacts as a result.

h) I liked the paper’s observation that California’s extensive system to transfer surface water actually amplifies the impacts of drought. Why is this? What is proposed by the authors as an alternative? (3)

Farmers can become dependent on this transfer of surface water, and transfers tend to be restricted during times of drought, which would then force farmers who depend on this transfer to reduce their farming activities. The authors suggest methods to facilitate recharge, including groundwater banking by using surface water to recharge groundwater. Groundwater is much less susceptible to evaporation loss than surface water, and by purposefully storing more groundwater farmers can have a more drought resistant source of water.