Geomorphology:
Groundwater Dynamics and Karstic Landforms

Introduction

Groundwater resources are important to mankind because of the large dependence of our civilization on this resource for not only domestic use, but also for manufacturing and irrigation. Groundwater is also vulnerable to contamination by waste chemicals and pesticides that are dumped onto the ground surface or into bodies of water by man. Much time and energy is invested into monitoring the quality of groundwater by state and federal government agencies so that this natural resource is not damaged beyond repair.

The proportion of a material that is void space is termed *porosity*. Note that this void space may be filled with a variety of liquid or gaseous materials such as water, atmospheric gases, or petroleum. The ability to transmit liquids via flow is termed *permeability*. The uppermost several kilometers of the lithosphere contain rocks of quite variable porosity and permeability. In general, sedimentary rocks have higher values of both and are, therefore, the most important reservoirs of groundwater. However, even igneous and metamorphic rocks, once they are fractured by physical weathering and unloading, will have some degree of porosity and permeability when near the surface.

Groundwater Characteristics

Groundwater is the water that occurs beneath the land surface inside small pore spaces in rock or soil. The underground surface that is defined as the place where pore spaces are completely saturated with water is termed the *water table*. Below the water table all pore space is completely filled by liquid water. The volume of rock that occurs below the water table is also referred to as the *zone of saturation*. The volume of rock that is above the water table is termed the *zone of aeration*. In the zone of aeration pore spaces may contain water but they are not completely saturated. The water table lies at varying depths below the surface of the earth, and is usually a subdued replica of the topographic surface. Since the water table is truly a surface, we can contour it just as we contour the land surface. Where the water table intersects the surface one may find a stream, lake or spring. Because groundwater is confined to the tiny pore spaces in a rock or sediment it does not travel as fast as runoff. Rates of movement may be as low as several centimeters per day. Therefore the *residence time* of water in the groundwater system is several orders of magnitude higher than that of runoff. This difference in the rate of movement has important consequences relative to pollution. Pollution of a stream system is usually immediately detected because of the rapidity with which the contaminate spreads throughout the downstream area. However, since groundwater moves slowly, the contamination of the groundwater may not be noticed decades after the actual contamination event. Another potential problem is the fact that groundwater resources are expensive to monitor because monitor wells must be drilled and maintained. This expense is an order-of-magnitude higher than that of sampling stream systems.

When precipitation is heavy over a period of time the soil horizon may become saturated throughout causing the water table to coincide with the topographic surface. The groundwater reacts to the force of gravity it begins to flow in the direction of the steepest inclination of the water table. This direction is the *hydraulic gradient*, which is analogous to topographic or stream gradients except that it refers explicitly to the water table surface. As water in the groundwater system drains away from topographically high areas the water table surface will become a subdued replica of the topographic surface. If the region undergoes a long period of drought, the water table will eventually become flat. In humid climates, however, the water table is usually in a state of flux between the extremes. The groundwater moving down the hydraulic gradient eventually encounters a location where the water table is elevated above the land surface. We term these areas ponds, swamps, lakes, streams, or sea level. In humid climates, much of the groundwater flows into stream systems via *effluent flow* a short distance from where the water infiltrated into the water table. Thus streams are to a large extent fed by effluent flow from the groundwater system in humid climates. Figure 11 displays the relationship of groundwater contours, groundwater flow direction, and effluent streamflow. Note that contaminated groundwater would move parallel to flow lines as an expanding *contamination plume*. The plume moves slowly while in the groundwater system, but will move rapidly downstream once the flow is fed into the stream. Also note that the flow lines are always in a direction perpendicular to the contours of the water table, and they move in a direction toward the lower contour line values. Note that the hydraulic gradient is easily calculated from water table contours since the map scale will determine the horizontal distance between two points on the surface, and the contour values will determine the change in elevation value.

Karst Landforms

In areas underlain by soluble rock - rocks easily dissolved by groundwater - typical landform features will develop that are characteristic of a *karst terrain*. When groundwater moves through limestone, the most common soluble rock, the natural acidity of the groundwater reacts with the $CaCO_3$ to produce Ca^{2+}, HCO_3^-, and CO_2 (carbon dioxide gas). This dissolution reaction produces large openings in the limestone termed *caverns*. If the cavern forms near the earth's surface, and it becomes relatively large, eventually the overhanging roof will fail producing a bowl-shaped depression on the surface. These landform features are termed *sinkholes* and they are very common in areas underlain by soluble rock. They are also the most distinctive landform feature of karst terrains. Since the bottom of the sinkhole may be below the current water table level, sinkholes are often filled with water to form ponds or lakes. If a stream happens to flow over a developing sinkhole, the water will be captured by the sinkhole and funneled into the water table. These types of streams are termed *disappearing streams*. Because of the streamflow capture, surface streams that extend for long distances are rare in karst landforms.

Over time the sinkholes will become larger. If several large sinkholes coalesce together in a linear geometry the resulting landform is termed a *solution valley*. Solution valleys have all the characteristics of fluvial valley systems except that the valley floor is filled with numerous sinkholes rather than a stream. Some solution valleys will contain a disappearing stream. After even more time several solution valleys will merge together so that the entire region is lowered by the erosion. At this stage the erosional surface may encounter different rocks that are not soluble. The normal fluvial stream valley landform features will then develop until another layer of limestone is encountered.

In the United States karst terrains are found wherever significant exposures of limestone occur. These areas include much of the states of Florida and Kentucky, and a good portion of north Alabama where Paleozoic carbonate rocks are exposed at or just below the erosional surface (see the Alabama State Geologic in the hall outside room #335). The term karst is derived from the region that lies along the Dalmatian coast of the Adriatic Sea. Quadrangles in our laboratory that display karst landform features include the Mammoth Cave, Kentucky 15° quadrangle and the Lake Wales, Florida 7.5° quadrangle. The presence of karstic landforms in arid climates, such as Carlsbad Caverns in southeast New Mexico, proves that these regions had a much more humid climate in recent geologic time.

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EXERCISE: GROUNDWATER SYSTEMS
Note: For this exercise you will need tracing paper.

Problem 1: Ashby, Nebraska 15' Sheet. This quadrangle map area is underlain by very porous sand and has sparse vegetation, therefore, precipitation in the form of liquid water infiltrates readily from the surface to the groundwater table.

a) Match the upper right corner of your 8.5 x 11" sheet of tracing paper with the northeast corner of the quadrangle. Your tracing paper should cover the approximate northeast quarter of the map area. Trace the lakes (blue) onto the tracing paper, including the lake elevations which are printed inside the lake boundary on the quadrangle. Assuming that the lake elevations represent the elevation of the water table, contour the water table using a contour interval of 5 feet. On your tracing paper label the value of each contour.

b) From the contour map determine the direction of groundwater flow (NE, E, SE, S, SW, W, NW, N).

c) If the owner of the Adams Ranch in section 34, T26N, R39W polluted the groundwater with pesticide is it possible that the Davis Ranch well (section 32, T26N, R38W) would be affected at some later date? Explain why or why not relative to parts (a) and (b).

d) Calculate the hydraulic gradient in feet per mile units from your contour map in part (a).

Problem 2: Lake Wales, Florida 7.5' Sheet. The bedrock of this map area is composed of limestone.

a) After observing the general features of this quadrangle, what term would best describe the landforms present in this area?

b) What is the term used to describe the lakes in section 35, T29S, R27E? How did they develop?

c) The area along the western margin of the quadrangle is relatively lower than the middle portion of the map. What is the landform term that best describes this area?

d) Examine the lake elevations throughout the map. Imagine the appearance of contours of the water table elevation. In what general direction would groundwater flow ? (N, NE, E, SE, S, SW, W, NW)?

e) If Lake Pierce was polluted with toxic waste, would the population of Lake Wales be affected if the local domestic water supply is Lake Wales? Explain your answer.

f) Using the southwest shoreline of Lake Pierce, and the northeast shoreline of Lake Wales, and the respective lake elevations of each, calculate the hydraulic gradient between these two lakes.

Problem 3: 3-point Problem from Figure 2.

A) Using a 3-point problem method determine the contours at a 10 foot interval for the water table using the below data. Assume that the water table is an unconfined inclined planar surface:

Well	Dept to Water	Well surface Elevation	W.T. Elev.
A	20 feet	_________	___
B	60 feet	_________	___
C	60 feet	_________	___

The contour lines in Figure 2 are topographic contours. Use these to estimate the elevation of the well head. Draw the water table contours at a 10 foot contour interval on the Figure 2 map and label each contour elevation.

B) What is the gradient of the water table in feet per mile? _______

C) How deep would a driller have to drill to reach the water table at point X ? ______

D) What is the azimuth direction of the groundwater flow? ______

E) If the groundwater below wellhead A was contaminated with pesticide which of the other wells would most likely be affected over time? _____

F) Green Pond is a source of municipal water. Is it possible for the pesticide contamination to affect this water supply over time? Explain.

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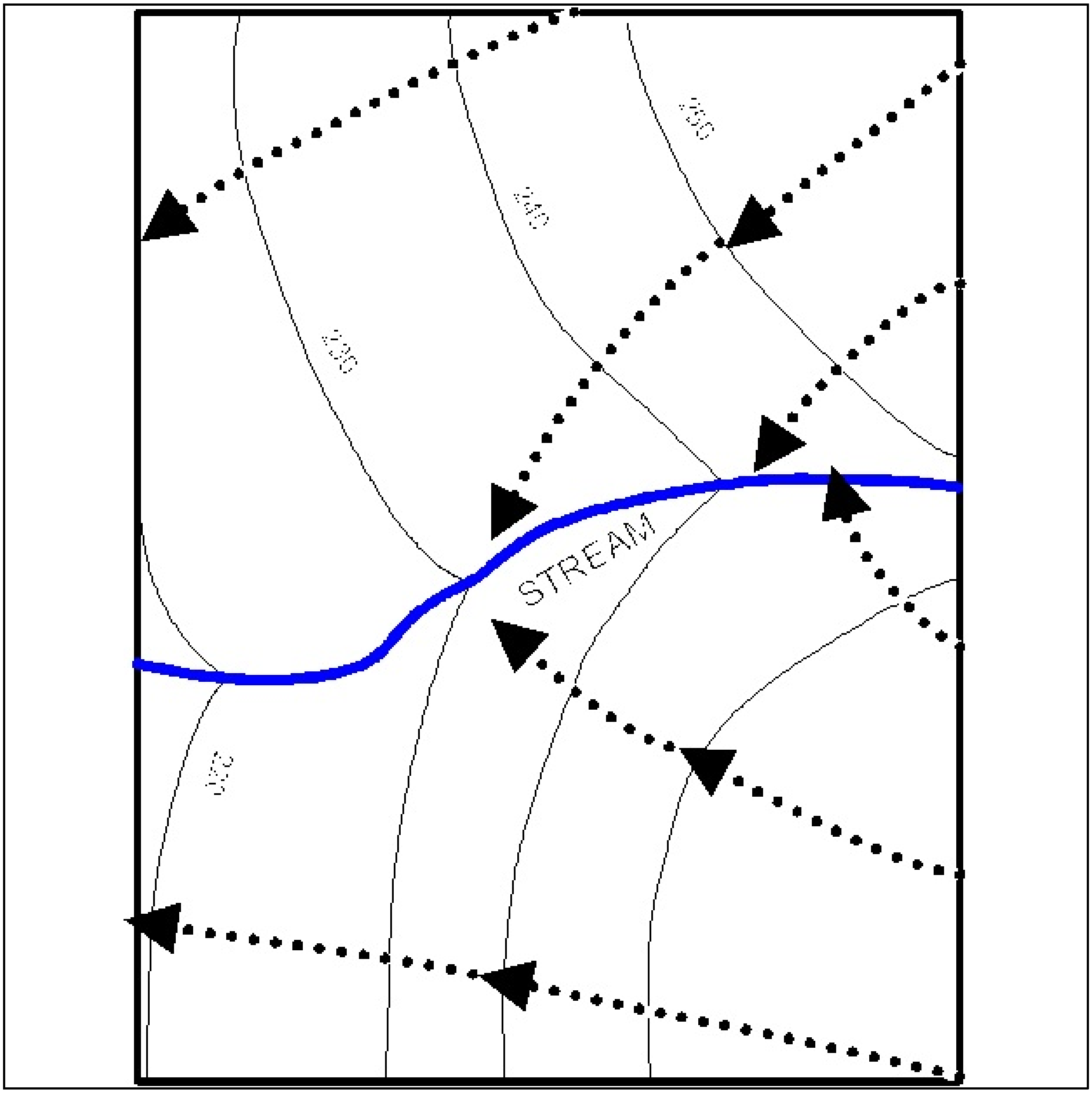

Figure 1. Hypothetical water table contours with superimposed flow lines (dotted line with arrows).

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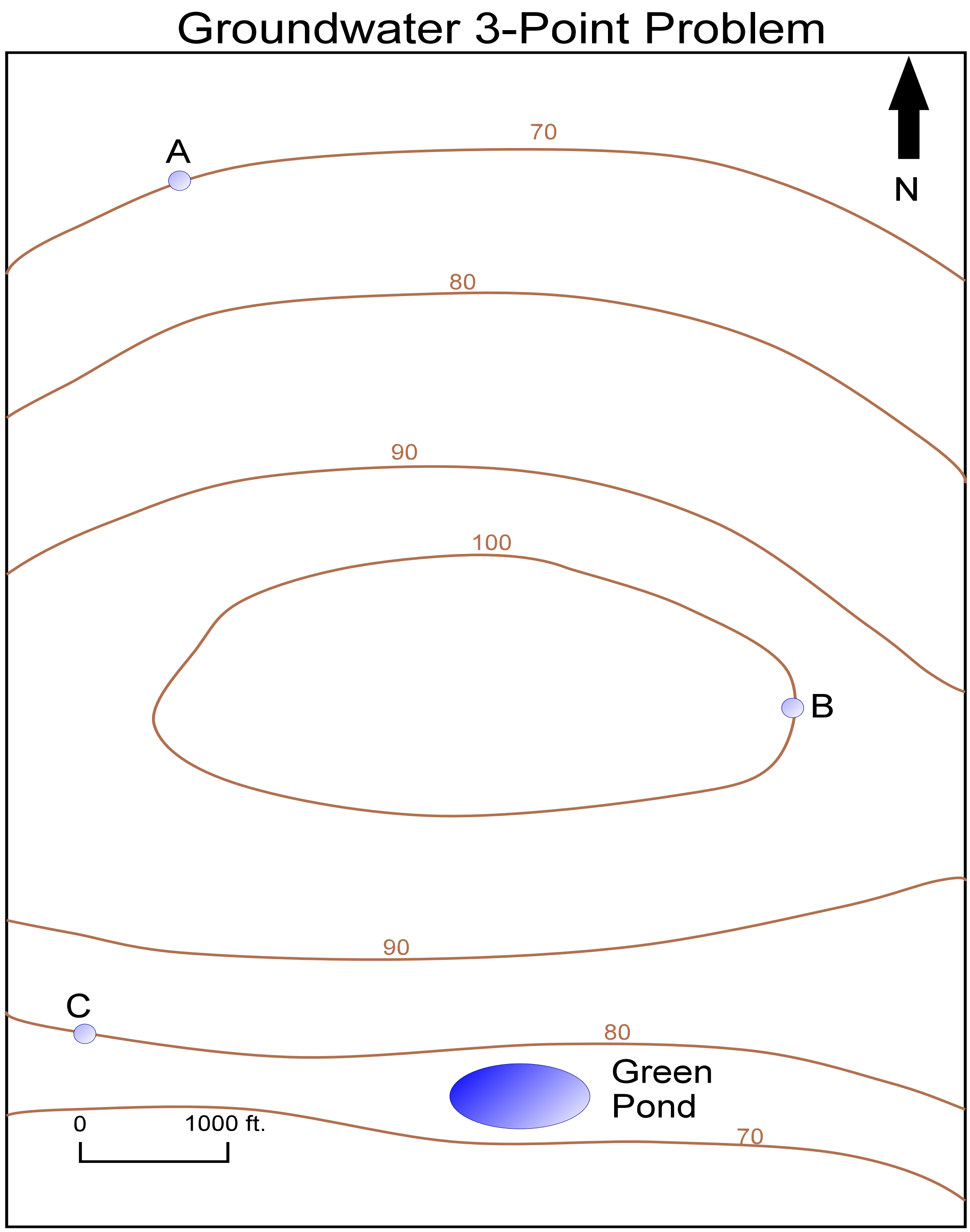

Figure 2: Groundwater 3-Point problem map.

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