Groundwater for Many People

The spatial science of a shared resource

— by Julienne Gard

Introduction

Problem

The fragile balance between groundwater supply and demand is being tested. Increasing rates of urbanization and irrigation place demands on water need, while the natural aridity of some environments does little to mitigate supply. In this lab, you will explore the spatial characteristics of this problem.

Location

The High Plains Aquifer that extends across Colorado, Kansas, Oklahoma, New Mexico, Nebraska, Texas, South Dakota, and Wyoming.

Time to complete this lab

The duration of the lab is one and a half hours to two hours.

Prerequisites

Students should have knowledge of basic computer processing. Necessary skills include opening files, saving files, word processing, and following software program instructions.

Data used in this lab

- URL for open source data access: **http://www.nationalatlas.gov/**
- Projection information: North America Datum 1983; geographic coordinate units are decimal degrees; ellipsoid model GRS1980

Student activity

Groundwater is critical for agriculture, drinking water, industrial use, and commercial use. Because it is naturally occurring and has so many uses, aquifer water is an extremely valuable resource.

View this video titled *Our Changing Planet*:
http://earth.rice.edu/MTPE/hydro/hydrosphere/hot/freshwater/OCP06_FreshWater.mov

As stated in the video, the High Plains (also known as the Ogallala) Aquifer is one of the largest in the world. Figure 1 shows its vast extent. It spans 450,000 km² across eight states, providing drinking water to an estimated 80 percent of people living within the aquifer boundary.

Groundwater aquifers store as much water as is placed into the basin. This replenishment occurs naturally and is called *recharge*. Natural recharge occurs when precipitation and stream flow replenish the water supply stored in an aquifer.

Figure 1. Extent of the High Plains Aquifer
[Source: USGS]

Figure 2 shows the recharge cycle. Rainfall infiltrates the soil to the water table, which naturally recharges the aquifer. As the image depicts, groundwater will replenish more quickly with more precipitation and with more porous (i.e., more permeable) soil grains. Precipitation cannot penetrate beyond the bedrock.

The recharge process takes time. Some water infiltrates down to the aquifer in a matter of days; sometimes this process can take years. For example, the Tucson, Arizona, Basin aquifer is still being recharged by precipitation that fell in the 1960s.
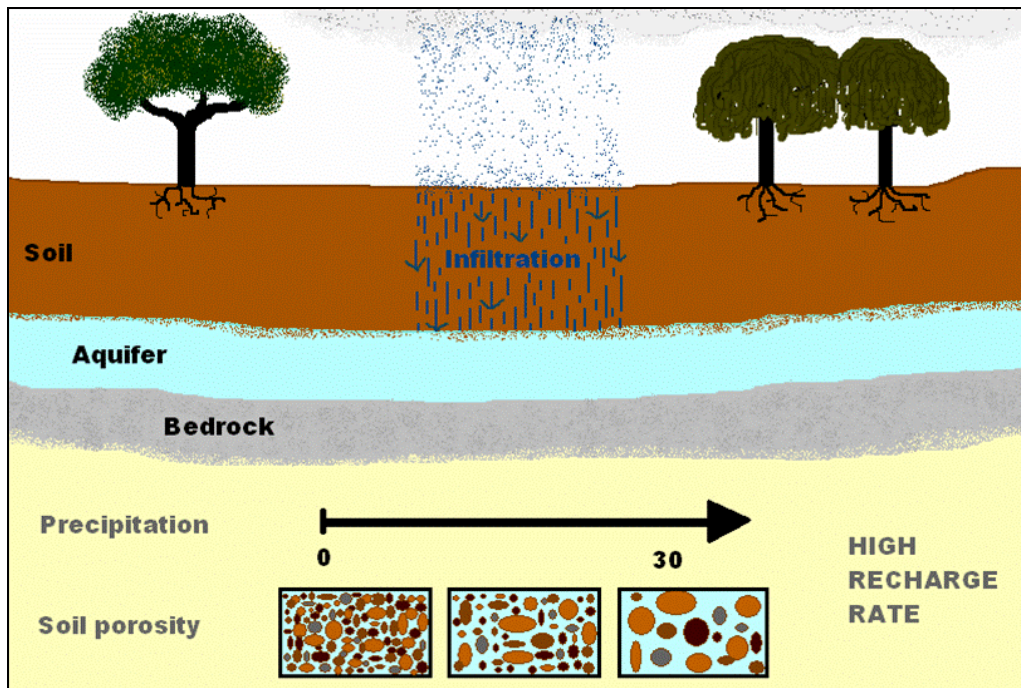

Figure 2. Recharge cycle

Figure 3 depicts the variance of precipitation across the United States. You now know that natural recharge occurs primarily due to rain. Because rain does not fall uniformly or with constant intensity, groundwater is replenished unevenly across space and time. Therefore, different places benefit differently from rainfall.

Using figure 3, focus on the eight states above the aquifer and think about precipitation variance.
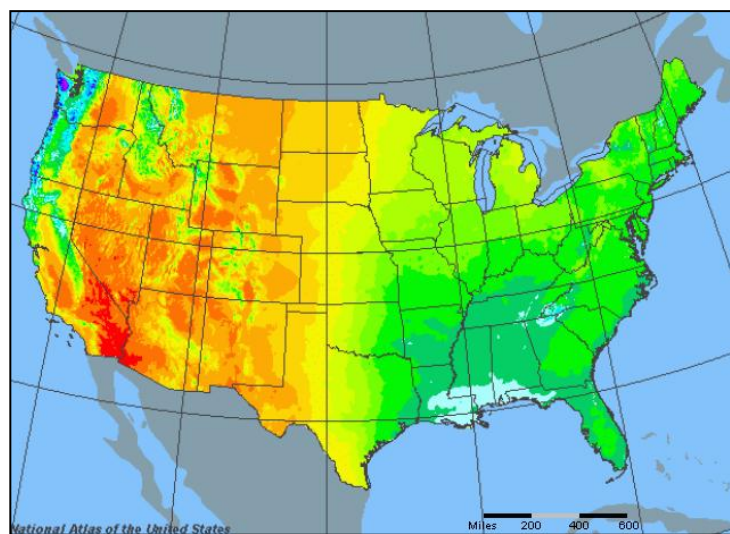

Figure 3. Precipitation averages [Source: National Atlas]

Figure 4 depicts the relationship between soil and porosity.

Soil granularity refers to the size of each grain, while their arrangement refers to how well they are sorted due to their size. Soil granularity and sorting influence how much pore space there is for water to penetrate. Thus, *porosity* determines an aquifer's ability to store water based on the amount of pore space in the sediment.

If an aquifer contains loose, porous rock material, there are more empty spaces (or pores) for retaining water. The opposite is true for compact sediments. The greater the porosity, the easier it is for water to infiltrate the soil. *Infiltration* is the critical process by which water (precipitation or otherwise) permeates the soil, moves downward to the water table, and refills the aquifer. Infiltration is necessary for natural recharge.

A) Evenly sorted sediments have high porosity
B) Poorly sorted sediments have low porosity
C) Evenly sorted sediments that are themselves porous have high porosity
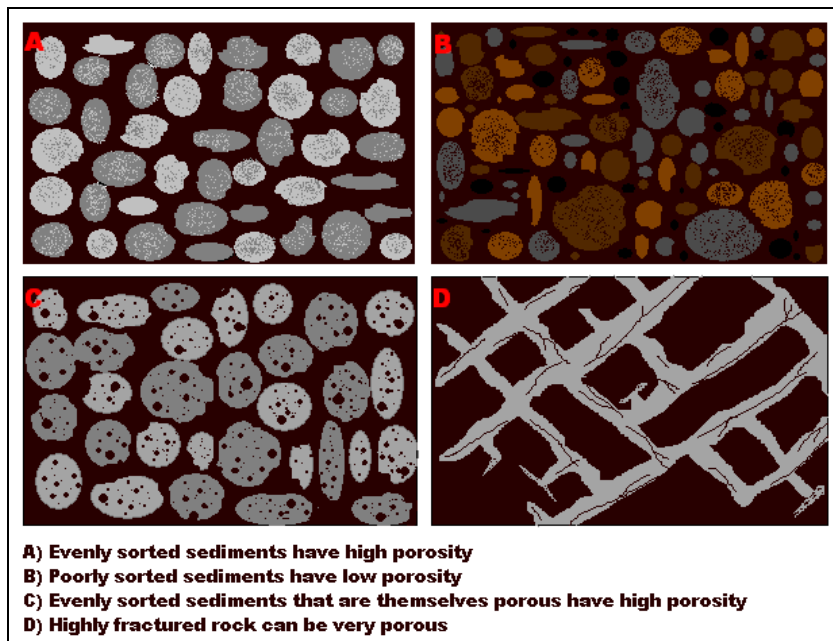**D) Highly fractured rock can be very porous**

Figure 4. The relationship between soil and porosity

As you see in figure 4, soil grains vary in size, shape, and degree of compaction.

Soils also have different temperatures, biotic material, and moisture levels. When scientists classify soils based on these characteristics, the soils are placed into types, or soil orders.

If you were to examine figure 4 on a larger scale, such as at a national level, you would be able to decipher spatial patterns. Soil types have spatial patterning, much like precipitation and groundwater, as discussed earlier.

Figure 5 displays dominant soil patterns in the United States. These spatial patterns are dominant because they can be explained by permanent regional characteristics such as climate, biological features, and topography.
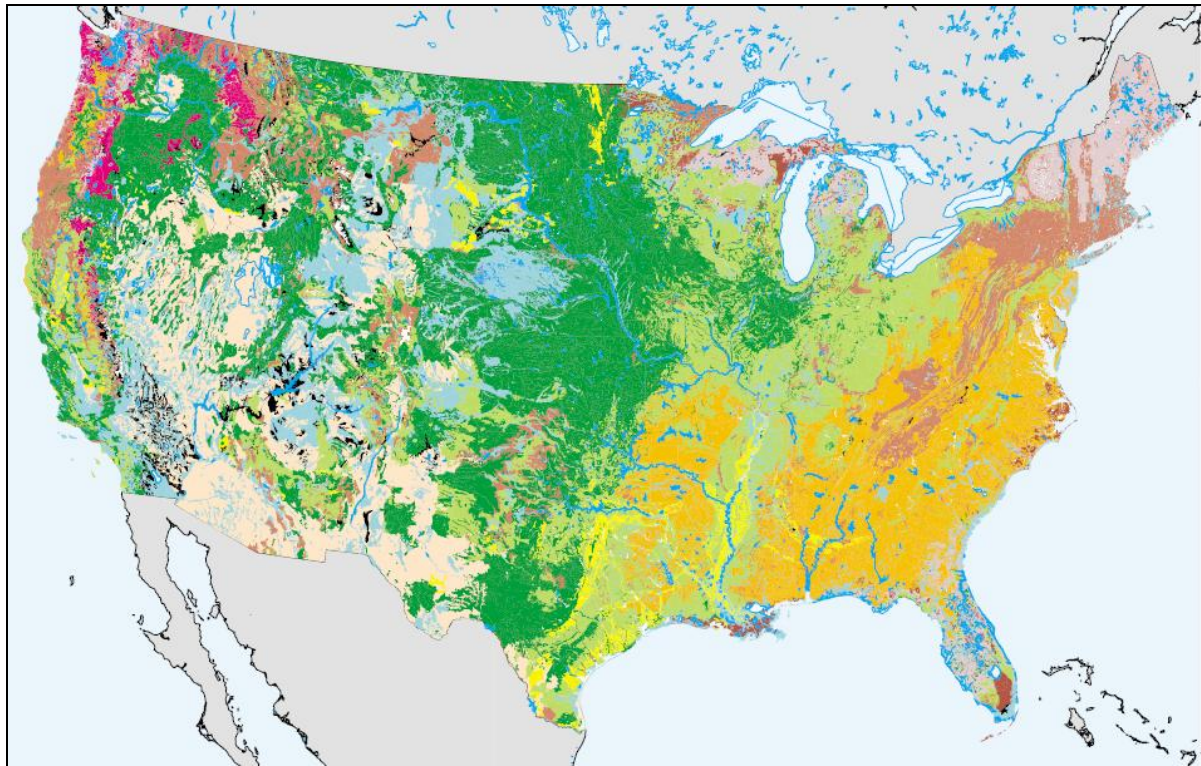

Figure 5. Dominant soils of the United States [Source: USDA]

Note in figure 6 that natural recharge must strike a balance between extraction and replenishment. Many of the world's aquifers are continuing to disappear. The consequences extend beyond loss of usable water.

One of the most destructive effects of overdraft is *compaction*. Compaction occurs when the water table drops and the sediments become compacted and less porous. The compressed rock material slows infiltration and reduces the aquifer's ability to store water. It is usually irreversible.

A derivative effect of compaction is *subsidence*. With the compression of underlying soil and rock, the ground surface above lowers. The subsided depression can range from a few centimeters to over a hundred meters.
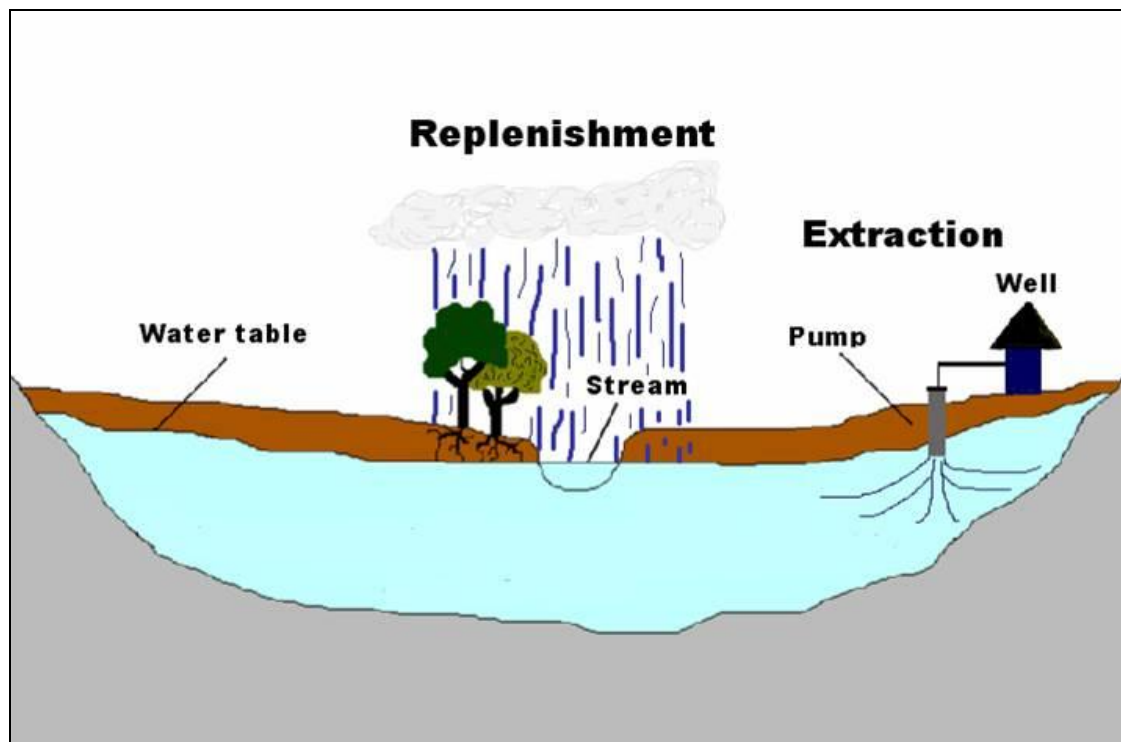
Figure 6. Balancing extraction with replenishment

Click the following link to view the video *Curious and Furious over Sinkhole,* which shows a news clip about devastating subsidence in Spring Hill, Florida.:
http://www.myfoxtampabay.com/dpp/news/local/sun_coast/Sinkhole_folo_050809

The sinkhole in the video was caused by overdraft and aggravated by drought.

As the above information suggests, groundwater equilibrium requires a critical balancing act. Because the physical and social geography of groundwater is rooted in spatial relationships, the use of spatial data, spatial reasoning, and mapping prove to be essential tools for managing this resource.

Today, you will conduct spatial analysis centered on the High Plains Aquifer groundwater source of the midwestern United States to identify water scarcity risk.

Using three primary variables and spatial analysis, you will identify urban areas at risk of water scarcity. The first variable, urban areas, represents highly populated places that consume large quantities of water. The second variable, counties that irrigate a large percentage of their crops by means of groundwater and surface water (e.g., lakes and streams), also constitutes water-stressed locations. The third variable, low average precipitation, represents limited capability to recharge the aquifer naturally. GIS functions such as clip, buffer, data classification, and query will aid you in identifying geographic areas most at risk, thus predicting a potentially devastating situation for many people.
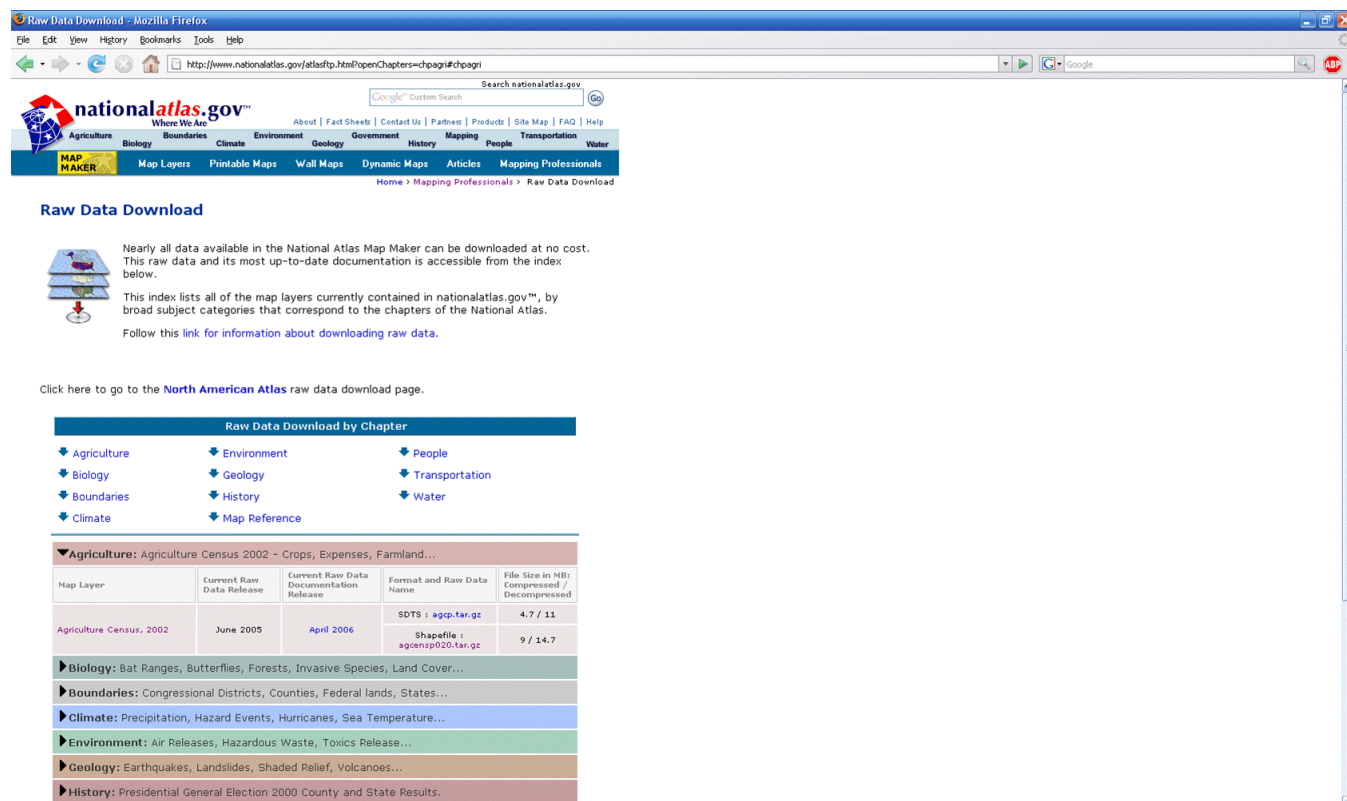
COLLECT DATA

1   Visit the National Atlas website at `http://www.nationalatlas.gov/`.

   To download data, click the *Mapping Professionals* link in the box at the upper right of the National Atlas home page.

2   Click the *Raw Data* link and click the *Water* tab.

3   Expand the list of available files.

4   Click the shapefile for data on "Aquifers."

   Note where this data is being saved on your computer.

5   Repeat this process for

   - "Agriculture Census, 2002" on the Agriculture tab
   - "State Boundaries" on the Boundaries tab
   - "Average Annual Precipitation, 1961–1990" on the Climate tab
   - "Urban Areas" on the Map Reference tab

6   Extract the data and save it to a secure space such as a USB device.

7   Before working with this data, examine the metadata downloaded with each shapefile. This text file (.txt) includes information about the source of the data and its coordinates, purpose, and attributes. It is good practice to familiarize yourself with data before commencing work.

Note that within this bundle, there is no presence of a projection file (.prj), meaning the data does not have a predefined projection. You will define those parameters in a moment.

PROCESS DATA

1   Launch ArcGIS.

2   Add only the aquifer data first. If the program alerts you to the fact that the data source you are adding has an unknown spatial reference, click *OK*. This issue will be addressed shortly.

Your view should look similar to the image below:
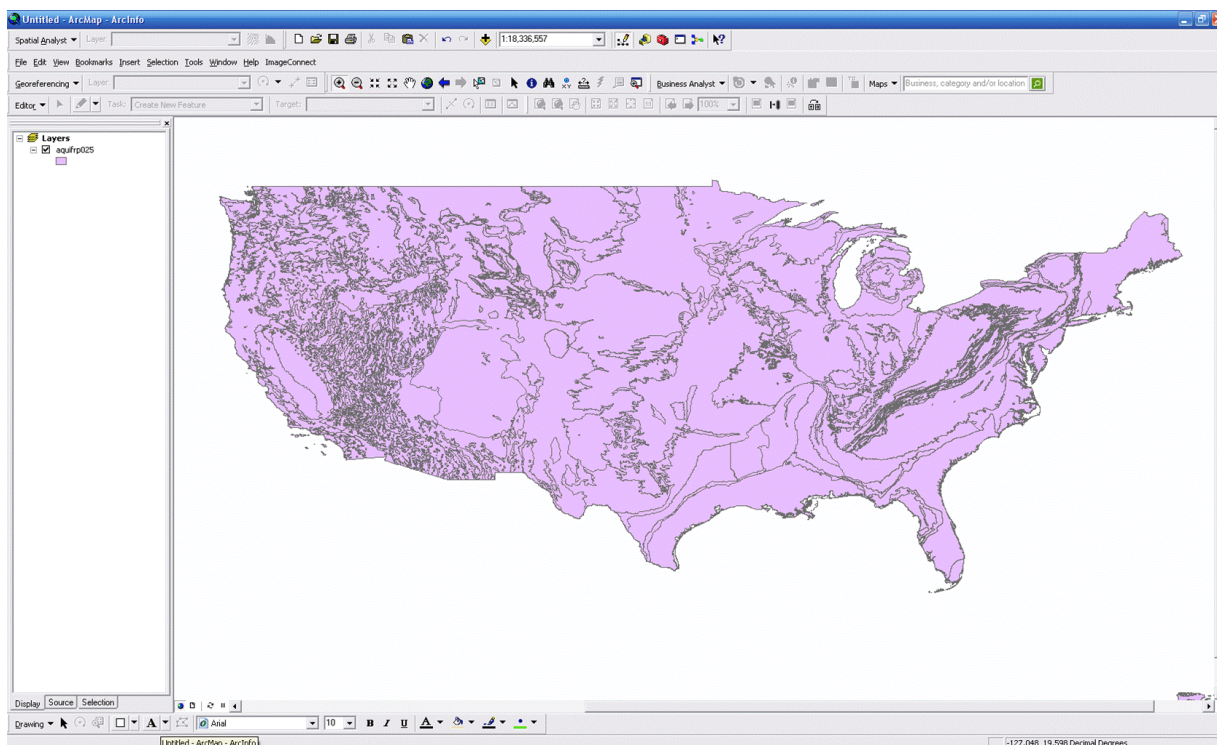
DEFINE A PROJECTION FOR THE DATA

1   Open ArcToolbox by clicking the red toolbox icon at the top near the center.

2   Expand *Data Management Tools*.

3   Expand *Projections and Transformations*.

4   Double-click the *Define Projection* button.

5   In the dialog box that opens, identify the *aquifers* file as the input.

6   To select a coordinate system from a preexisting list, click the button to the right of the drop-down menu. The *Spatial Reference Properties* dialog box opens.

7   Navigate to *Geographic Coordinate Systems, North America*, then *NAD 1983*.

8   Click *OK* until the program tells you the function was successful.

9   Repeat these steps for each subsequent data layer you add.

ANALYZE

CREATE A NEW LAYER

The High Plains Aquifer is our study area. Create a new layer that comprises only this aquifer by querying the data.

1   Click the *Selection* menu and choose *Select by Attributes*.

     You will create a new layer from the Aquifer layer.

2   Choose the aquifer shapefile in the drop-down menu for *Layer*.

3   Double-click the field *AQ_NAME*.

4   Click the equals button (=).

5   Finish the statement by clicking the *Get Unique Values* button and double-clicking *High Plains aquifer*.

6   Click *OK*.

     One aquifer should now be selected in your view, as shown in the map below.

7   To create a layer from this selection, right-click the aquifers layer in the table of contents, scroll to *Selection*, and choose *Create Layer From Selected Features.* This automatically adds the new layer to your view. Rename this layer *High Plains Aquifer*.
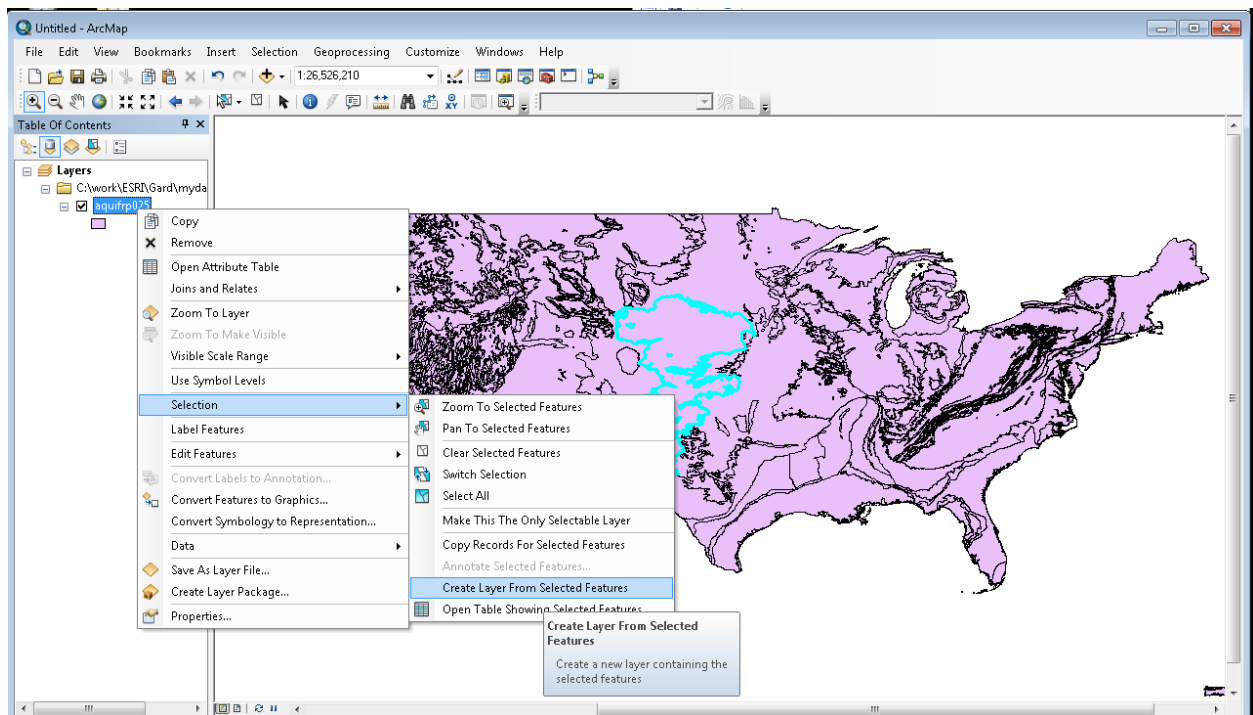
8   Remove the original aquifers layer from the map, since it now only provides superfluous data.

9   Add the remaining four shapefiles to your view. Do not forget to define the projections as you did with the first aquifer layer (see steps listed above).

10 To more easily differentiate between the data layers, change the titles and colors to more appropriate options such as those seen below:
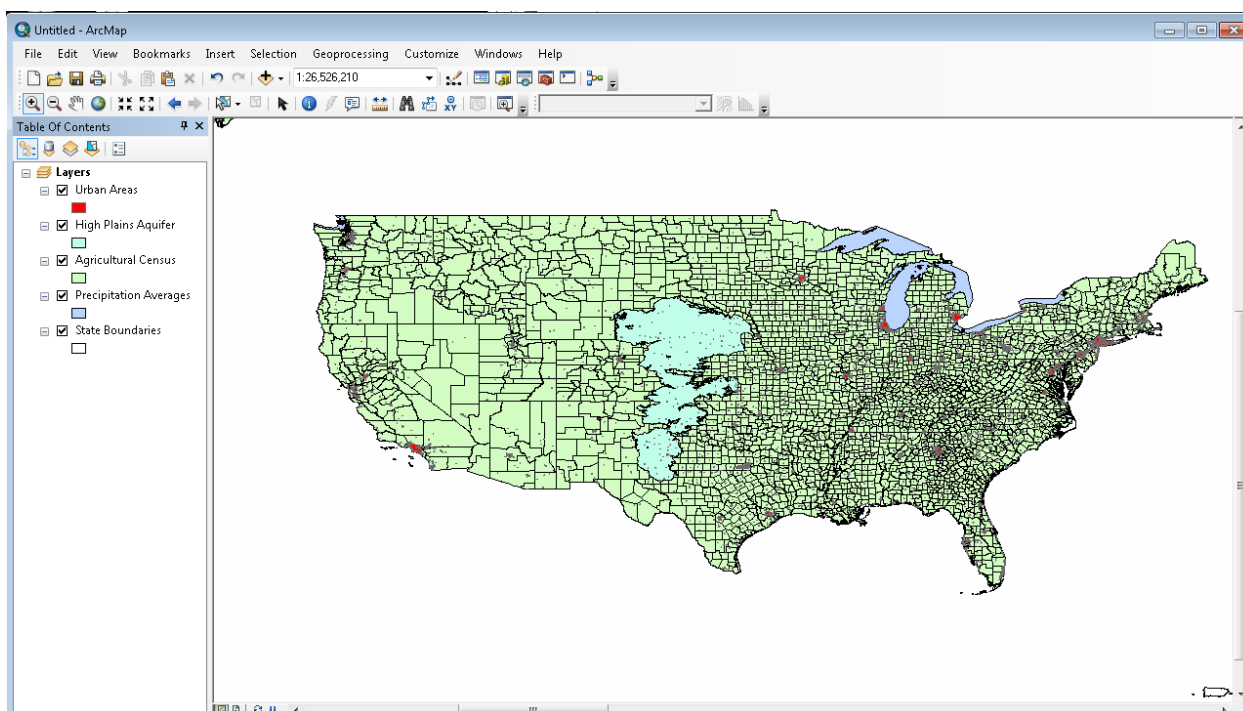
11 Drag the new *High Plains Aquifer* layer to the top of the table of contents and change its transparency to 50 percent so that the other layers are visible (Hint: Find this function in the layer's *Properties* on the *Display* tab).

CHANGE HOW PRECIPITATION IS CLASSIFIED AND DISPLAYED

The next step in data preparation requires you to change the way the precipitation data is classified and displayed.

1 Double-click the *Precipitation* layer to open the *Properties* dialog box.

2 Click the *Symbology* tab.

3 Show *Graduated colors* under the *Quantities* option (on the left side of the dialog box).

4 Select *RANGE* as the *Value*.

5 Select an appropriate color ramp (such as the one displayed in the map below).

6   Keep the classification as *5 Natural Breaks* (see Help for more information on classification).

7   Click *OK*.
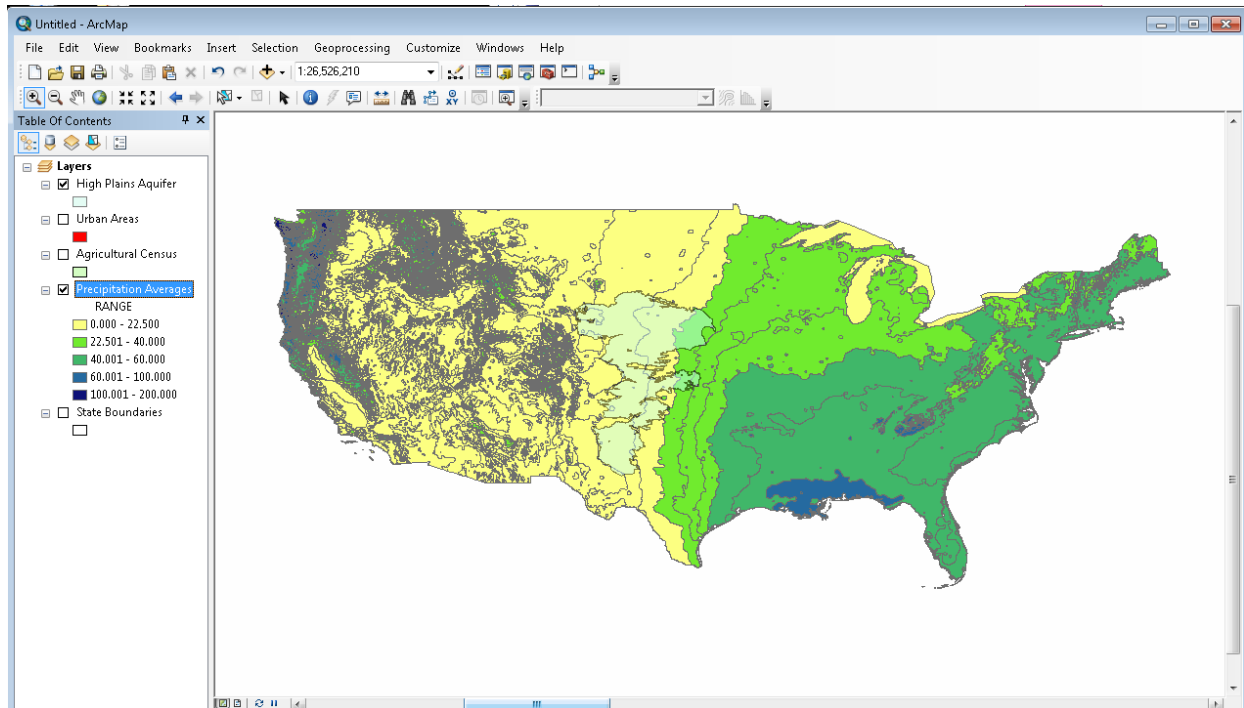
Question 1: *Note the spatial pattern of precipitation across the United States. Now consider these same patterns over the Ogallala Aquifer. How might the precipitation patterns you see over the aquifer affect its natural recharge?*

IDENTIFY DEPENDENT AGRICULTURE

Agriculture in this region of the country is highly dependent on this groundwater source. To find out how many counties are heavily reliant on it, you will conduct another simple query.
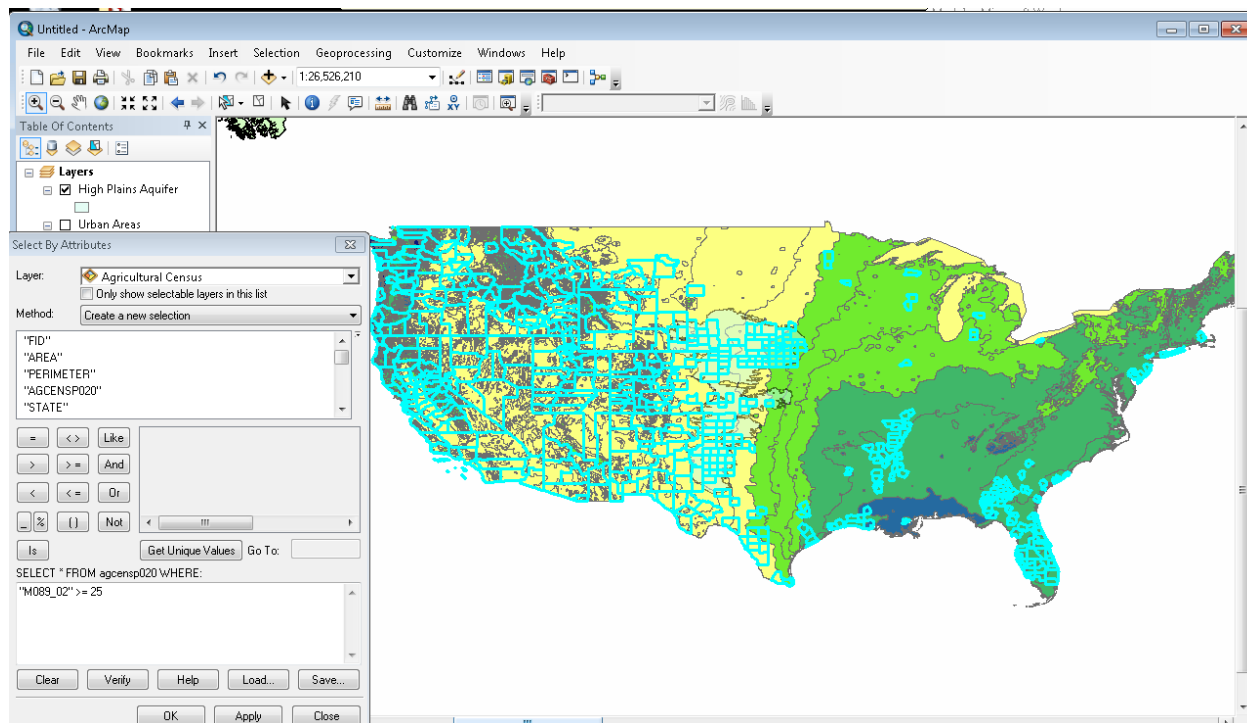
1   Click the *Selection* menu and choose *Select by Attributes*.

You will create a new layer from the *Agricultural Census* layer.

2   Choose the *Agricultural Census* shapefile in the drop-down menu for *Layer*.

3   Double-click the field *M089_02*.

4   Remember to examine the metadata that downloaded with the shapefile for descriptions and definitions.

5 Click the *greater than or equal to* (*>=*) button.

6 Finish the statement by typing the number *25*.

7 Click *OK*.

The query you wrote identifies the counties that irrigate 25–100 percent of total harvested cropland acreage. Roughly 830 counties should be selected in your view, and your map should resemble the image below:

8 To create a layer from this selection, right-click the *Agricultural Census* layer in the table of contents, scroll to *Selection*, and choose *Create Layer From Selected Features*. This automatically adds the new layer to your view. Rename this layer *Counties That Irrigate More Than 25%*.

Question 2: *When visualizing the precipitation variable and new greater than 25 percent irrigation layer simultaneously, what spatial relationship do you see?*

IDENTIFY LOW PRECIPITATION

To better visualize the groundwater supply and demand of this region, you will now introduce another variable: low precipitation.

1   Click the *Selection* menu and choose *Select by Attributes*.

You will create a new layer for low precipitation using the *Precipitation Averages* layer.

2   Choose the *Precipitation Averages* shapefile in the drop-down menu for *Layer*.

3   Double-click the field *RANGE*.

4   Click the *less than or equal to* (<=) button.

5   Finish the statement by typing the number *22.5*.

6   Click *OK*.

The query you wrote identifies the precipitation bands that range from 0 to 22.5 inches annually, as seen below:
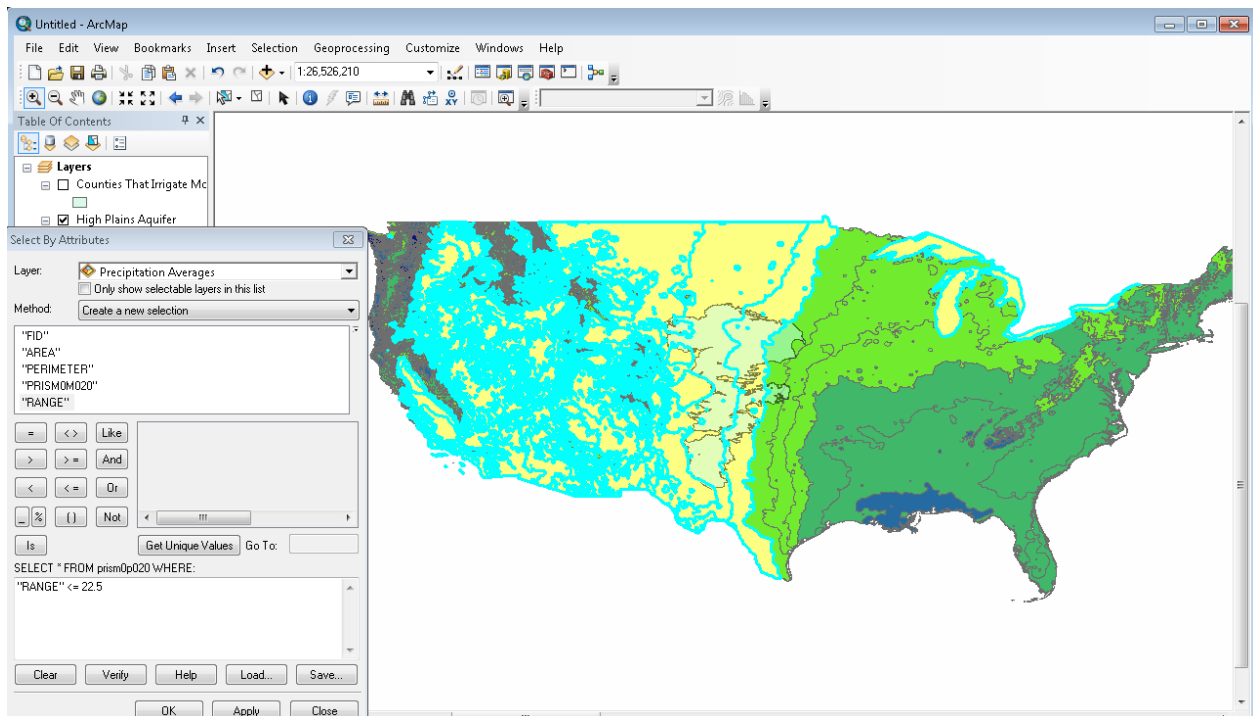
7   To create a layer from this selection, right-click the *Precipitation Averages* layer in the table of contents, scroll to *Selection*, and choose *Create Layer From Selected Features*. This automatically adds the new layer to your view. Rename this layer *Low Precipitation Averages* (*0–22.5 Inches*).

ANALYZE THE WATER SUPPLY

To conduct analysis on water supply proximal to the aquifer, you will now perform a buffer analysis:

1   Open ArcToolbox.

2   Expand *Analysis Tools*.

3   Click the *Proximity* tab.

4   Double-click the *Buffer* function.

5   Select *High Plains Aquifer* in *Input Features*.

6   Name your output feature class *150 Mile Buffer*.

7   Set the distance to *150 miles*.

8   Click *OK*.

The result should resemble the image below:
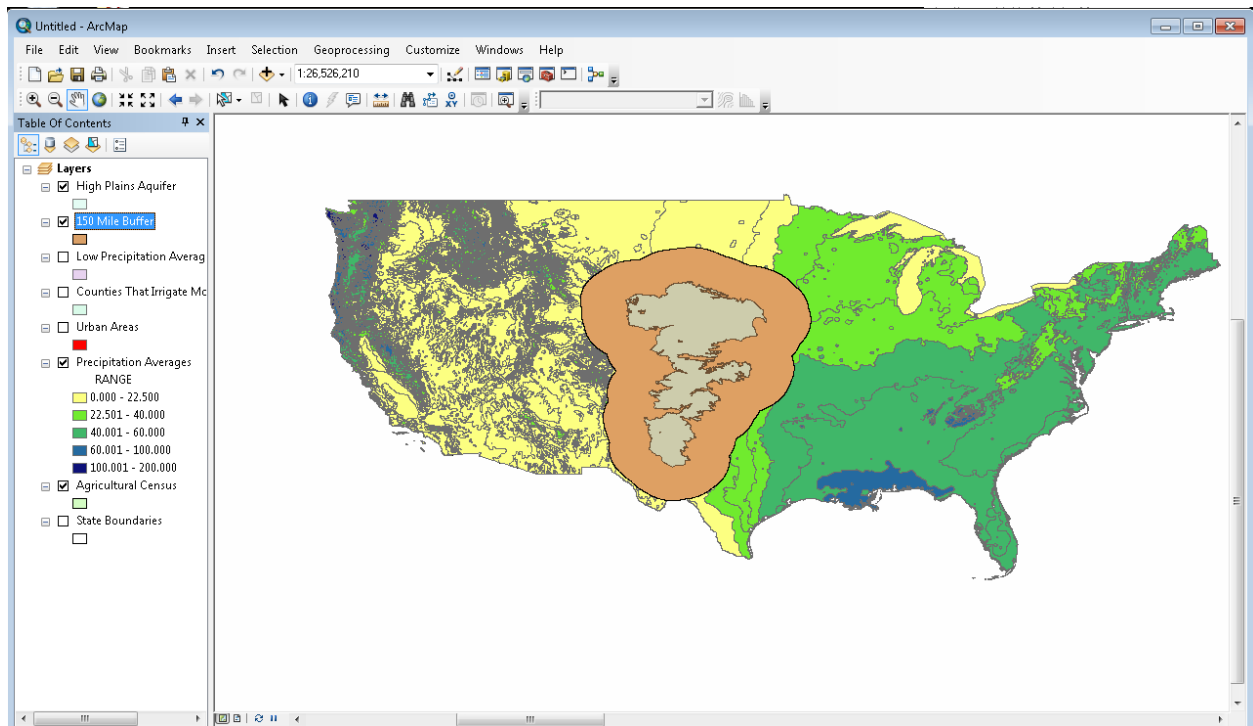
To narrow your focus in preparation for the next analytic step, you will select the urban areas that fall within the buffer.

9   Open ArcToolbox.

10   Click *Analysis Tools.*

11   Click the *Extract* tab.

12   Double-click the *Clip* function.

13   Select *Urban Areas* in *Input Features.*

14   Select *150 Mile Buffer* in *Clip Features.*

15   Name your output feature class *Urban Areas within Buffer.*

16   Click *OK.*

By making the buffer 50 percent transparent and turning off the original layers, your view will be more focused.

IDENTIFY AREAS MOST AT RISK

You are now prepared to make the final query identifying the urbanized locations that are reliant on the High Plains groundwater and most at risk of losing this resource.

Using the urban areas layer clipped in the last step, you will identify those locations that intersect counties that irrigate more than 25 percent of their crops. Both variables are indicative of high water use and, thus, risk.

1   Click the *Selection* menu and choose *Select by Location*.

        You will create a new layer for urban areas that intersect irrigation-reliant counties.

2   Choose *Select features from* in the first drop-down menu.

3   Check the box next to the *Urban Areas within Buffer* layer.

4   Select *Counties That Irrigate More Than 25%* in the second drop-down menu.

5   Select *intersect the Source layer feature* in the last drop-down menu.

6   Click *OK*.

7   Create a new layer from the selection (see Help or instructions above).
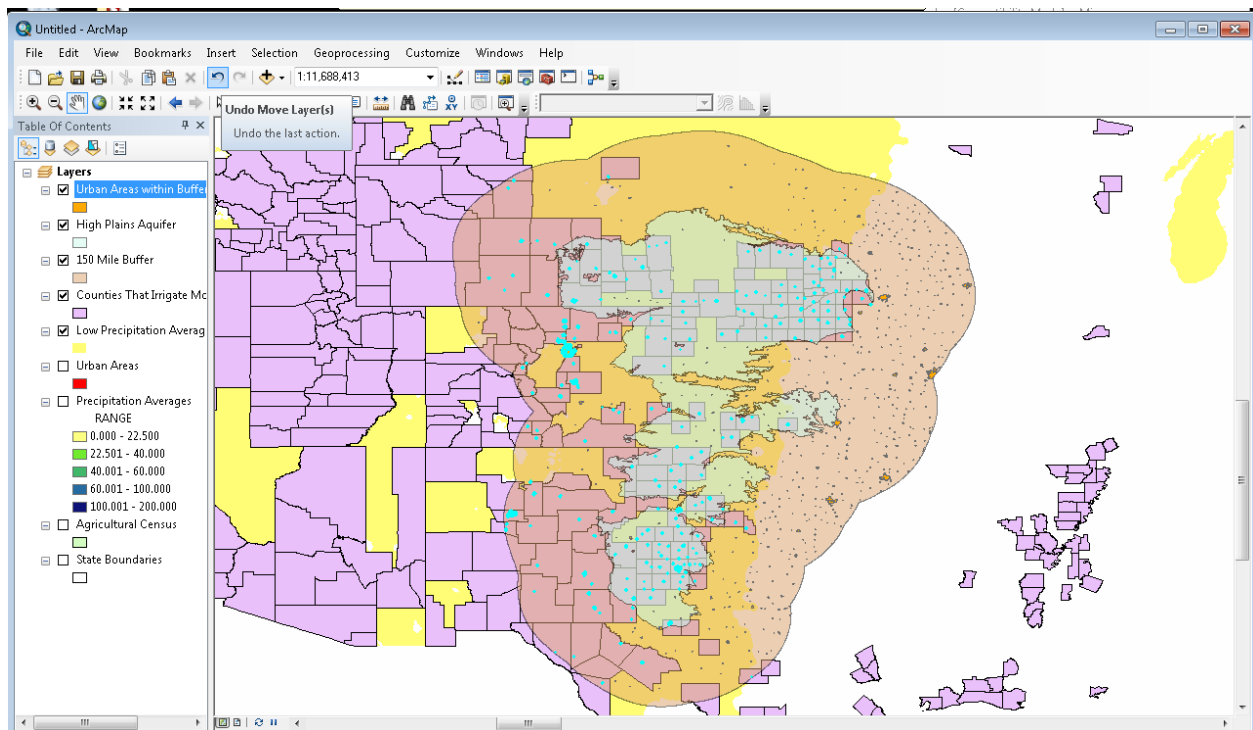
Repeat this selection process but with minor changes:

8 Check the newest layer that you created for the first drop-down input.

9 Select *Low Precipitation Averages* for the second input.

10 Select *are within the Source layer feature* (instead of intersect) in the last drop-down menu.

11 Click *OK*.
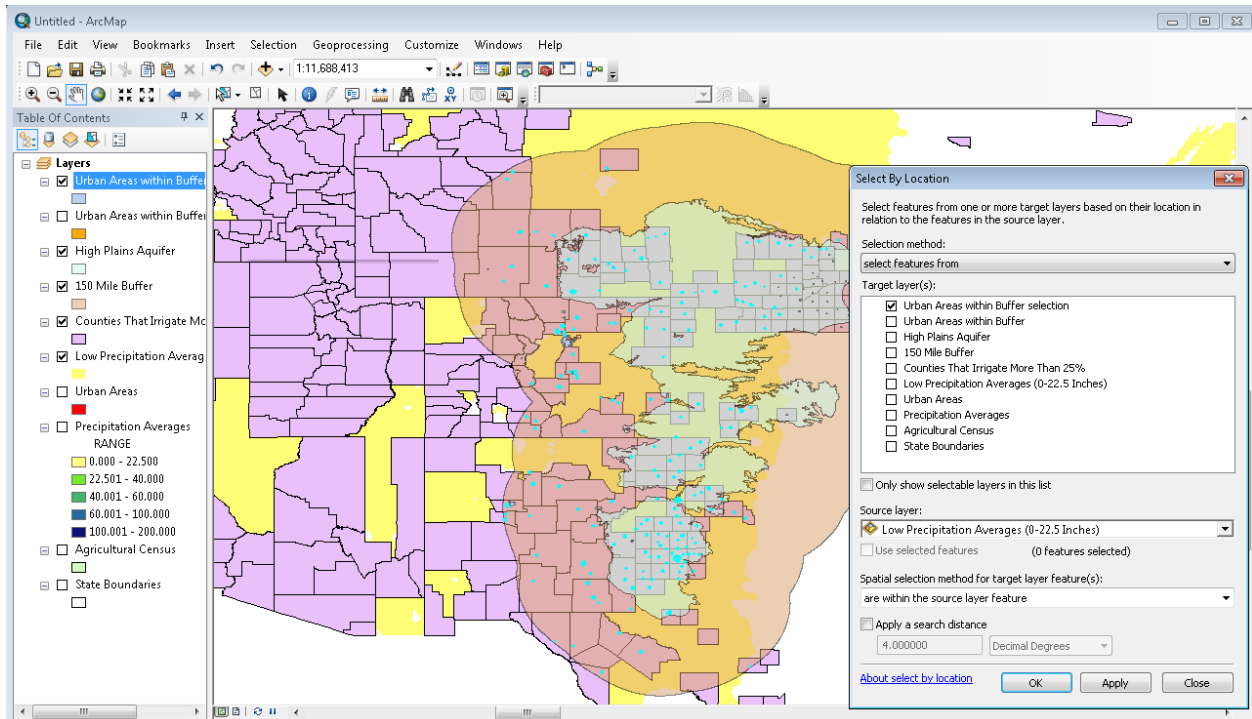
The urban areas (home to the greatest populations) that have been selected as a result of this query are at greatest risk of water scarcity. They are at most risk for three reasons: (1) Urban areas represent large, water-needy populations; (2) these areas exist in counties that use vast quantities of the groundwater to irrigate; and (3) they exist in climates that receive little precipitation to recharge the source.

12 Rename the new layer and change the color to an appropriate (i.e., bright) hue. The result should resemble the image below.

13 For geographic reference, turn on the states layer.
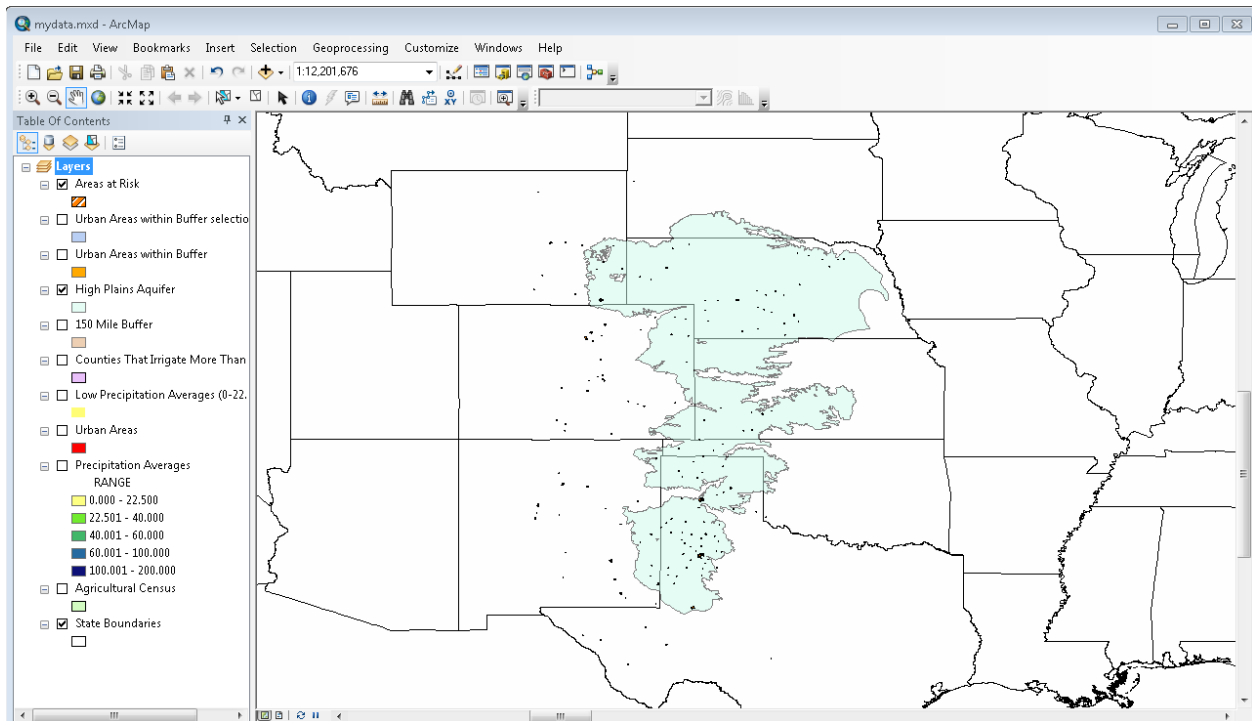
Question 3: *How many urban areas are at risk?*

Question 4: *Which states need to be most concerned with this issue with regard to their urban environments?*

Question 5: *Groundwater sustainability is clearly an interdisciplinary science. Name two ways spatial thinking serves as a useful tool in this context.*

Conclusion

There are clearly multiple variables associated with groundwater, which means that planning for appropriate supply and demand (and dealing with important issues such as pollution) requires large-scale public policy intervention.

Click the following link to view the video, *Groundwater and Public Policy*:
http://www.esi.utexas.edu/outreach/groundwater/videos.php?vid=pol&res=lo

This video demonstrates that groundwater management, in this case of the Edwards Aquifer in Texas, is a multifaceted task that requires planning at many levels. Politicians, scientists, urban planners, economists, and residents must work together to ensure that they maintain the natural balance of this critical resource.

The questions posed in this lab present an incomplete picture of the issues associated with the High Plains Aquifer. You considered only the social repercussions of water scarcity. Consider, however, the possibilities of analyzing groundwater contamination, using the *National Atlas* dataset Arsenic in Ground Water, as another disadvantage of overdrafting. Alternatively, you could predict when a

county or state will exceed its carrying capacity using 2010 projected population data from the American Community Survey (`http://www.census.gov/acs/www/index.html`).

A more physical geography question could identify areas at risk of subsidence using what you know about porosity and a soil layer from the United States Department of Agriculture (`http://soils.usda.gov/survey/geography/ssurgo/`). To examine the change over time in actual agricultural production, use census data such as that displaying crop and farm productivity for the years 1992, 1997, 2002, or 2007 (`http://www.nationalatlas.gov/mld/agcn07.html`).

In any case, spatial thinking enables analysis that accounts for numerous variables—social, environmental, fiscal, political, and so on—that coexist in space and time.

Submit your work

Print the final map and attach it to your responses to the questions.

Credits

Images

Figure 1: courtesy of U.S. Geological Survey.
Figure 3: courtesy of U.S. Geological Survey.
Figure 5: courtesy of U.S. Department of Agriculture, Natural Resources Conservation Service

Instructor resources

Updates for 2013 edition

This lab activity has been updated to work with ArcGIS 10.1.

Visualization and analysis tools

For Esri ArcGIS version 10 and higher

Contextual information

The High Plains, or Ogallala, Aquifer is one of the largest underground water sources in the world. In the United States, it is responsible for roughly 30 percent of all irrigated crops and provides 80–90 percent of the drinking water for people that live in its region. But beyond these statistics, the High Plains Aquifer is also a painful example of a world teetering on the edge of environmental ruin.

Because rates of withdrawal are exceeding replenishment, hydrologists estimate that this resource is being depleted at a rate of several feet per year. At such a rate, this late Miocene feature may disappear in under 40 years.

Figure 2 displays the High Plains Aquifer's vast spatial extent. Suggest to the students that there are many political, social, and economic implications to sharing a common resource that has no spatial boundaries to reflect political demarcation. Unlike mineral deposits or forests, which are stationary, water is a fluid resource that travels across political boundaries.

Ask students to consider the problems that might arise from this sharing of a common resource such as groundwater. Who should regulate usage and pollution across state lines? Why is pollution a particularly difficult groundwater issue? Which party should pay for water monitoring, cleaning, and recharge?

When looking at figure 6, remind students that the rate of infiltration varies across space as a function of the soil. Direct their attention to the soils of the Great Plains region overlying the High Plains Aquifer. The students should not be concerned with learning the different soil orders but should be able to visually interpret what the spatial variation means for the High Plains Aquifer.

Given that you now know something about the permeability of the soil types, how is this map useful to groundwater science? In particular, think about relationships between soil porosity and what this means for recharge.

The second video, *Curious and Furious over Sinkhole*, demonstrates a case where a social need (water) and a physical vulnerability (geologic compaction) spatially intersect in a way that is detrimental.

Tell students that some spatial connections are clearly positive. For example, the spatial intersection of some bat species and mosquitoes means that a natural predator-prey relationship occurs. For humid places with high and vulnerable populations, this intersection of features might indicate a decreased incidence of malaria because the mosquito disease vector is controlled by the bats.

Spatial thinking helps us understand these relationships and question their patterns. Spatial analysis can then be used to analytically predict, monitor, and prevent disastrous events such as the one reported by Fox News. Being able to utilize all your data at one time is invaluable to effective management.

In the third video, *Groundwater and Public Policy*, Professor Butler uses the term *carrying capacity*. What do you think this means in the context of a limited resource? Explain that *carrying capacity* is an ecological term referring to the number of individuals that can be sustained in a place given the natural resource limits, such as water.

References

Dennehy, K. F., D. W. Litke, and P. B. McMahon. "The High Plains Aquifer, USA: Groundwater Development and Sustainability." *Geological Society, London, Special Publications* 193: 99–119. Journal article providing an overview of the history and future of the High Plains Aquifer.

Alley, W. M., and S. A. Leake. 2004. "The Journey from Safe Yield to Sustainability." *Ground Water* 42(1): 12–16. Journal article about groundwater sustainability and the importance of integrated scientific approaches.

Fayer, M. J., et al. 1996. "Estimating Recharge Rates for a Groundwater Model Using a GIS." *Journal of Environmental Quality* 25: 510–518. Journal article that illustrates how GIS might be used to explore the other side of the issue not addressed in this lab: supply/recharge.

Video from University of New South Wales, Australia, on the sustainability of groundwater use (`http://www.connectedwaters.unsw.edu.au/resources/video/tvgroundwater.html`).

Website from Texas Tech University that stores data and maps about the High Plains Aquifer (`http://www.gis.ttu.edu/OgallalaAquiferMaps/`).

Website maintained by the *National Atlas* offering interactive mapping with many variables (`http://nationalatlas.gov/mapmaker`).

Website maintained by the Kansas Geological Survey offering Internet-based mapping functionality with data regarding the High Plains Aquifer (`http://www.kgs.ku.edu/HighPlains/index.shtml`).

Spatial GIS data bank maintained by Nebraska Spatial Data Bank
(`http://dnr.ne.gov/databank/spat.html`).

Data information

The data provided by the *National Atlas* originates from the United States Census Bureau or United States Geological Survey. All datasets are downloaded as compressed files and have detailed metadata attached in a text document.