Measuring Water Resources Unit 3: Groundwater withdrawal and fluctuations in the height of Earth's surface student exercise

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Complete this lab working with a group of three. You will hand in your own lab answer sheet, but some of the answers will provided by your group members.

I. Background

The boundary between the North American and Pacific Plate runs through California. The Plate Boundary Observatory (PBO) network was developed to monitor this plate boundary. The PBO GPS network consists of over 1000 operational GPS sites, many located in California (https://www.unavco.org/instrumentation/networks/status/pbo/gps).

Although originally installed to study plate tectonics, the PBO network has recently been used to study the terrestrial water cycle (Amos et al., 2014; Borsa et al., 2014; Chew and Small, 2014). When water loading at the Earth's surface increases, the Earth's crust and mantle compress elastically – the surface of the Earth moves downward. In contrast, the surface of the Earth moves upward when water loading decreases.

One of the most significant ways that humans affect the distribution of water mass at or near the surface of the Earth is through pumping of groundwater, primarily for irrigated agriculture. Some irrigation water returns to aquifers via infiltration. However, most of the groundwater used for irrigation is transferred to the atmosphere via evapotranspiration. The Earth responds elastically to the mass loss caused by groundwater withdrawals and moves upward. So, it is possible to monitor the effects of groundwater pumping on terrestrial water loading using GPS vertical positions. Regions with considerable groundwater mining have strong negative gravity anomalies, so the effects of groundwater withdrawal can also be detected from space using the GRACE satellites. However, GRACE data has very coarse spatial resolution, so it is only possible to identify regional-scale changes in water storage.

However, there is one important complicating factor – which is the focus of this lab. Local subsidence is possible when water is withdrawn from the subsurface. Two different processes affect aquifer systems as groundwater is removed. First, as pore pressure drops, rearrangement of aquitard sediments causes irreversible compression (Galloway et al., 1999). This leads to permanent subsidence over timescales of years to decades. Changes in pore pressure also yield instantaneous and reversible ***poroelastic effects***: as pore pressure drops (increases), the sediment matrix compacts (expands) and the surface elevation decreases (increases). ***This poroelastic adjustment has the opposite effect on surface height from elastic changes in the Earth's crust and mantle caused by changes in terrestrial water storage: a decrease in groundwater storage corresponds to a lower surface elevation.***

In this lab, we will use GPS data from California to evaluate how groundwater withdrawals result in vertical displacement at the Earth's surface. In what locations is the elastic response to mass loss the dominant process? Where is local subsidence from compression and poroelastic effects greatest? We will compare the magnitude of displacement resulting from these two opposing factors. Other processes that change hydrologic loading (e.g., drought) may also influence the records of surface displacement, so these must be considered as well.

II. The Data

GPS records from nine PBO stations are provided (Table 1). You will work in a group of three – each of you will analyze data from three of the sites and share their results with others in the group. The GPS sites are split into three groups for you. Each person should select one group and proceed.

Table 1. Station name and location for nine PBO sites in California. Answers for vertical trend and timing of peak in seasonal cycle should be inserted into this table as you arrive at the answers working through exercise's questions.

	Station	Latitude	Longitude	Vertical Trend (mm / yr)	Month of peak in seasonal cycle
Person 1	P536 P056 P567	35.28 36.03 35.42	-120.03 -119.06 -118.75		
Person 2	P538 P303 P570	35.53 37.05 35.67	-120.11 -120.71 -118.26		
Person 3	P539 P307 P572	35.70 36.95 36.59	-120.18 -120.06 -118.95		

1. Locate your three stations on the Google Earth map. Now mark the locations of all nine stations on the geologic map of California that is included with this lab. You do not need to be exact – the goal is to see how the stations are located relative to each other and the physiography of California. For each site, predict the geologic materials you would find beneath the GPS station. What type of rock or sediment underlie the site? Also, what is the topography of the site? You may find Google Earth the best tool to answer the second question. Provide this information in the space below.

Station 1:

Station 2:

Station 3:

III. Data analysis

You will be making six graphs of vertical position through time. For each of the three sites, you will graph vertical position through time and detrended vertical position through time. Two graphs per site (combine each site onto one page). Details for each graph are as follows. You will hand these three pages in as part of your answered lab.

2. Open up the file that includes daily records of vertical position from all nine stations. Make a graph of vertical position (in mm) as a function of time (in years) for each of your three stations. Make sure each graph has appropriate x and y-axis labels, as well as a title indicating which station it is.

3. Now, make some observations about the time series from each of your three stations. Describe any key features (seasonality, magnitude of movement up or down) of the time series in the space below.

Station 1:

Station 2:

Station 3:

4. For each station, calculate a trend from the vertical position data. The trend is equivalent to the slope of the best-fit line to the data. Excel has a slope function [=slope(y's, x's)]. Please report the trend in units of mm/yr? Write your calculated trends in the appropriate column of summary table. Add the corresponding values from the other six stations to the table (provided by those in your group). How well does the best-fit line conform to the data? Are there any large differences between the line and the data (aka residuals)? Add any observations about the residuals in the space below.

Station 1:

Station 2:

Station 3:

5. For each of your three stations, add a new data column and fill it with a ***detrended*** time series of vertical position. This detrended data shows the differences between observed vertical position and the trend through time. Make three graphs of the detrended data and place them on the same page as the original plot for each site.

6. Now describe the detrended time series. What features do you observe on the graphs of detrended vertical position. Are seasonal variations apparent? If so, what month of the year is detrended vertical position highest (add this to the summary table)? Are there features in the graphs other than seasonal fluctuations? We will hypothesize what these might be indicative of below.

Station 1:

Station 2:

Station 3:

IV. Interpretation and Discussion

In this section of the lab, you will compare the records from the nine sites, identify similarities and differences between them, and explain your observations in terms of hydrologic process.

7. Work with your partners in the group. Can you split the 9 sites into two (or more) distinct groups based on the characteristics of variations in vertical position? Consider both the original and detrended data as you work. In the space below, describe the characteristics or signatures you are using to identify the distinct groups, and list which stations are included with each group. Also choose and draw a symbol that will be used to indicate the grouping for your map of the stations (for example, a box, or an x…..).

Group 1:

Group 2:

Group 3: (if needed)

8. Now return to the map of California and mark each site with a symbol indicating what group the site belongs to (for example, a square, or an x…..).

IV. Summary and conclusions

9. Now we hypothesize how groundwater pumping affects vertical position of the two groups. For each group of sites you identified based on similarities in behavior, describe how groundwater withdrawal affects vertical position. Are both groups affected by the elastic response to a decreasing hydrologic load? What about sediment compression and poroelastic effects? How do seasonal fluctuations in water storage affect the time series from each group? Are effects of the 2012-2016 drought apparent? Consider both the original and detrended data.

10. Summarize your answer by providing a conceptual diagram for each group of sites. Provide arrows showing the relative size of each effect where present: elastic response of the crust and mantle, poroelastic effects, and irreversible sediment compression. Include text to describe the various elements of your diagram.

11. **Reflection**: What do you think are the most important strengths and limitations of monitoring groundwater storage changes using variations in vertical position recorded by GPS instruments? Describe the strengths and limitations via a comparison to both traditional and other geodetic tools (like GRACE) for monitoring groundwater storage.

V. References Cited

Amos, C. B., Audet, P., Hammond, W. C., Bürgmann, R., Johanson, I. A., & Blewitt, G. (2014). Uplift and seismicity driven by groundwater depletion in central California. *Nature*.

Borsa, A. A., Agnew, D. C., & Cayan, D. R. (2014). Ongoing drought-induced uplift in the western United States. *Science*, *345*(6204), 1587-1590.

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