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Comparison of Methods to Assess Groundwater in Pennsylvania

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Motivation

In many parts of the world, groundwater is being, or on the way to being, overexploited for human use. Moreover, the response of groundwater to changes in climate or land use is not well understood. One of the key causes of the gaps in our understanding of groundwater behavior is the lack of groundwater level data. This has led to attempts to develop surrogate methods to estimate changes in groundwater levels. A comparison of a few of these methods was conducted for selected watersheds in Pennsylvania.

Theory

Recession flow analysis has often been used to estimate aquifer properties. Brutsaert and Nieber (1977) showed that that several well-known solutions of the Boussinesq equation can be expressed in the form

$$\frac{dQ}{dt} = aQ^b$$

where Q is streamflow, t is time, and a and b are "constants".

Rearranging, the above equation would be written in logarithmic form as

$$\ln\left(-\frac{dQ}{dt}\right) = \ln(-a) + \ b\ ln(Q)$$

The linear solution of the Boussinesq equation for "long-time" outflow is given by

$$b = 1$$

$$a = -\Pi^2 k_0 p D L^2 (n_e A^2)^{-1}$$

where k_0 is the saturation hydraulic conductivity, p is an empirical weighting constant, ranging roughly between 0.3 and 0.4, D is the aquifer thickness, n_e is its drainable porosity, L is the total length of all tributary and main river sections upstream from the gauging station, and A is the area of the catchment.

Since the coefficient a is directly proportional to the aquifer thickness D, it has been suggested (e.g. Lyon 2009) that changes in a can be interpreted as change in the aquifer thickness. Thus an increase in the intercept of the log($-dQ/dt$) versus log(Q) plot would correspond to an increase in aquifer thickness, or an increase in the groundwater level.

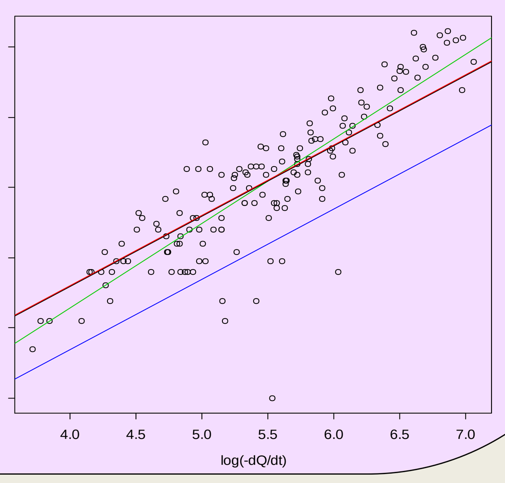

Figure 1: Example ln(-dQ/dt) v ln(Q) plot for one five year period for a stream gauge in the study. The lines are best fits for: b = 1 (black) , b = 1 but with data "binned" into twenty equally spaced intervals (red), b = 1 lower envelope (blue), simple linear regression (green). In this case, the binned and "unbinned" lines are close.

Data and Methods

24 watersheds which had both groundwater and streamflow data for a period of 30 years or more were selected. The streamflow gauges selected were determined to be relatively free of human influence. Because of the presence of multiple gauges in many watersheds, daily data from a total of 31 streamflow gauges and 32 groundwater gauges were available for the selected watersheds. In order to avoid influences from snow and ice, the date range of April 15 - October 31 was chosen. The periods of analysis varied (starting between 1957 and 1976, and ending between 2000 and 2011) and were determined by groundwater gauges in a watershed since these have the shorter record.

Trends in depth to groundwater were calculated by using the mean depth to groundwater for each year for years that had data for at least 80% of the days in the 4/15-10/31 period for the year. For streamflow, the 7-day low flow for each year was determined by selecting the lowest average flow to occur over the course any 7 days. Recession flow analysis was conducted using data from moving windows of 5 years. To reduce the influence of precipitation, only recessions longer than 6 days were selected, and the first 4 days of each recession excluded. Various methods have been previously suggested for determining the location of the line through the log($-dQ/dt$) versus log(Q) plot. As detailed below, a number of these methods (Fig. 1) were used in this analysis.

Results: Recession flow analysis

The trends in log(-a) for lines with b = 1 and (a) passing through all points, (b) passing through data "binned" into twenty regular intervals, (c) forming the lower envelope of points (i.e. had 95% of points above) are shown below. As can be seen (Fig. 2), the selection of method plays a visible role in the trends observed.

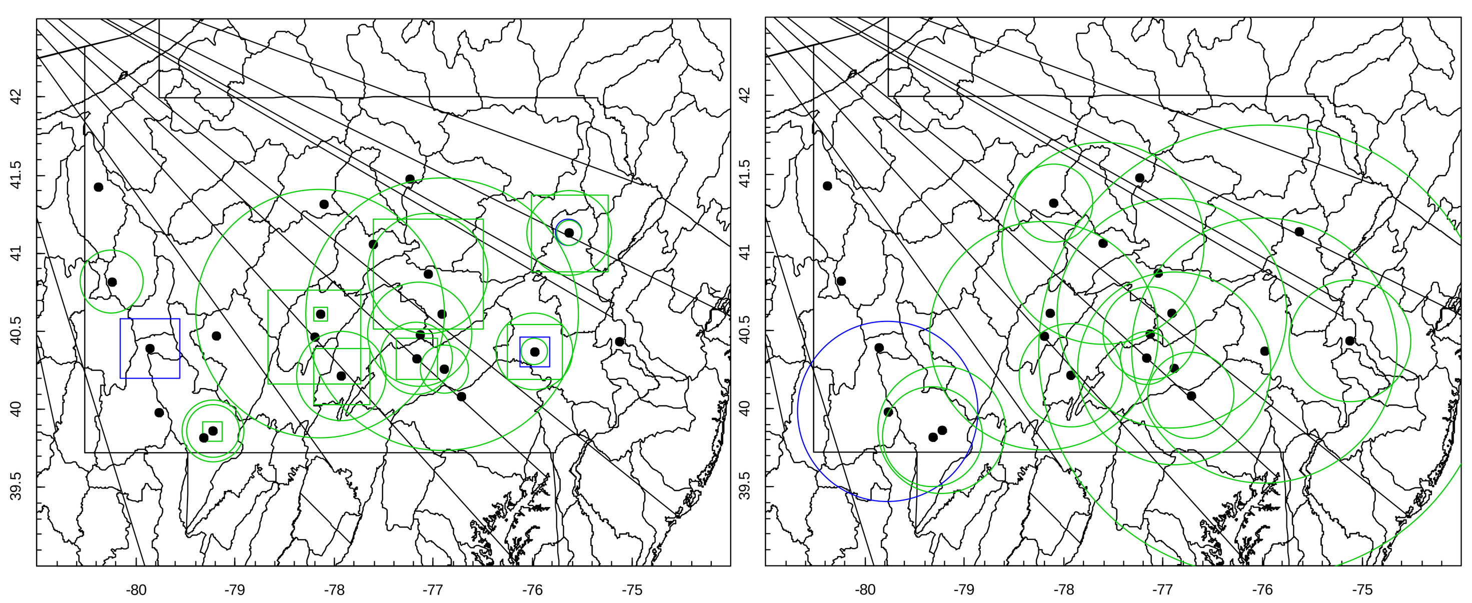

Figure 2: Left- Trends in log(-a) determined by line passing through all points (circles) and binned data (squares). Blue indicates decreasing trend, green indicates decreasing. The size of the symbols indicates relative magnitude. Black dots indicate location of gauges. Right - Trends in ln (-a) as determined by the lower envelope.

Results: Low flows

Only one stream gauge (Fig. 3) was found to have a significant trend in 7-day low flows (for the period of analysis; longer term data indicate these have generally increased).

Results: Groundwater

Both decreasing and increasing trends are seen in depth to groundwater (Fig. 3). There is some correspondence with gauges with changes in log(-a), but this is not universal. Notably, the number of stream gauges with decreasing log(-a) regardless of specific method is far greater than groundwater gauges with increasing depth to groundwater. There is little correspondence with the 7-day low flow.

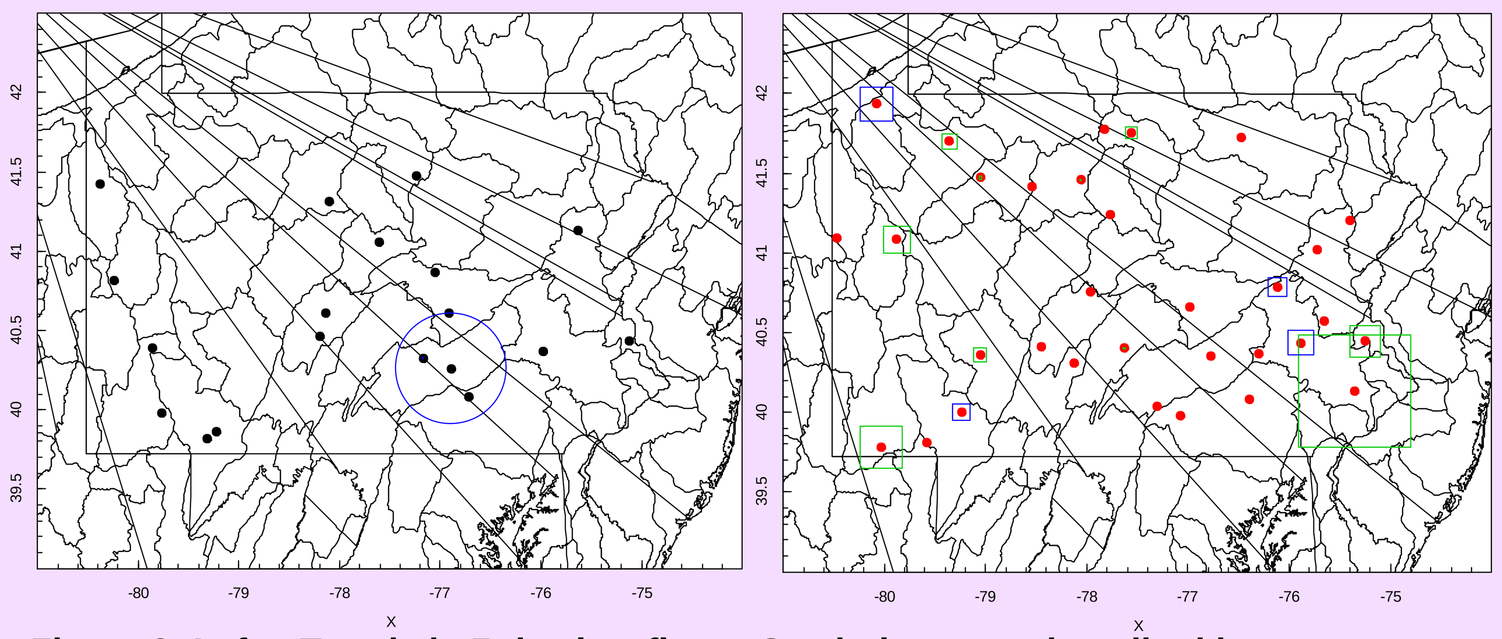

Figure 3: Left – Trends in 7-day low flows. Symbols are as described in Figure2. Right - Trends in *depth to* groundwater. Symbols are as described in Figure2.

Conclusions

This simple study ignores hydrogeology, precipitation, evapotranspiration, etc. Despite these limitations, it does seem to indicate that different methods give results that can be quite different. The need for reasonable estimates on changes in groundwater in the absence of groundwater level data has lead to alternative attempts as substitutes. This study shows however that caution is needed in drawing conclusions using these indirect methods. It is possible that these different methods can be reasonable substitutes for each other, however further research is needed in establishing the conditions under which this would be the case.

The mean value of b, when not fixed at 1, varied between 1.07 and 1.78 (standard deviation 0.04 – 0.49), and showed an increasing trend for many gauges. This and the widespread decreasing trend in log(-a) warrants additional investigation.

References
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Lyon, S. W. et al. Hydrol. Earth Sys. Sci. **13**, 595-604 (2009).

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