Using coupled hydrogeophysical modeling to assess the likely value of proposed gravity observations to support water resources decision making

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Abstract

Decisions regarding the permitting of new groundwater extractions often depend on the perceived impact of those withdrawals on groundwater levels in wells and flow in nearby streams. These decisions can be informed using an ensemble modeling approach, which quantifies both the most likely outcome and the associated uncertainty given limits on subsurface hydrogeologic information. Additional data can constrain forecasts, thereby improving decision making. Groundwater levels in wells are one of the most common hydrologic measurements; but, it can be prohibitively expensive to drill wells to add new observation points to inform decision making. Time-lapse gravity measurements provide a proxy method to gain insight into the subsurface hydrologic conditions. While gravity measurements are less direct than groundwater levels, it can be considerably less expensive to add monitoring points. In this study, an ensemble of MODFLOW models is developed for a hypothetical catchment. Forecasts of drawdown in one well due to the addition of another well are the prediction of interest for decision making. The accuracy and uncertainty of the forecasts are calculated with and without added observations. The result is a map of the basin showing the relative expected value of an added observation at each location for improving the prediction of interest. This map can be used to choose among monitoring locations before data are collected. The same approach could be extended to consider multiple measurements of different types.

Introduction

The gravitational attraction between two masses is:

$$g = \frac{G * m_1 * m_2}{r^2}$$

where G is the gravitational constant, m_1 and m_2 are the masses and r is the distance between the centers of mass of the two objects. In this model, m_1 is assumed to be the instrument and negligible compared to the mass of the water in the subsurface. So the equation can simplify to an expression of only the (change of) mass of water in the subsurface. Gravimeters only measure the gravity in the vertical direction, g_z, giving:

$$g_z = \frac{\sqrt{(Z_o - Z_c)^2}}{r} * \frac{G * m}{r^2}$$

Using this equation, the expected gravimeter response can be calculated at any location on the ground surface. Further, the change in gravity at a location can be calculated from two output times of the groundwater flow model. In this case, we calculate the gravity response with and without the town well for each model and compare it to a 'truth' model to assess model likelihoods. Then we can use these likelihoods to calculate an ensemble-average drawdown at the town well if an agricultural well were added. Comparing the likelihood-weighed average to the true effect of the ag well for each monitoring location defines the added value of that location for the prediction of interest.

Methodology

1) Use a python code to generate a model ensemble;
2) Model each scenario with MODFLOW to get steady state head values throughout the domain for three different time periods (no town no agriculture, yes town no agricultural, and yes town yes agricultural);
3) Eliminate nonbehavioral models;
4) Choose one model (not in the ensemble) as a truth model and calculate the error in predicted drawdown at the town well due to the ag well for each model (repeat this using each model as the truth model);
5) Calculate the gravity change before and after adding the town well at each location for each model, then use the mismatch between this gravity change and that of the truth model to calculate the likelihoods of the models in the ensemble;
6) Calculate the likelihood-weighted forecast of the impact of the ag well for each possible gravity measurement location and assign the error in this prediction to the measurement location;
7) Average the mismatch over all of the truth models to define the average forecast error for each measurement location and also calculate the variance of these mismatch values to assess the uncertainty of the forecast error.

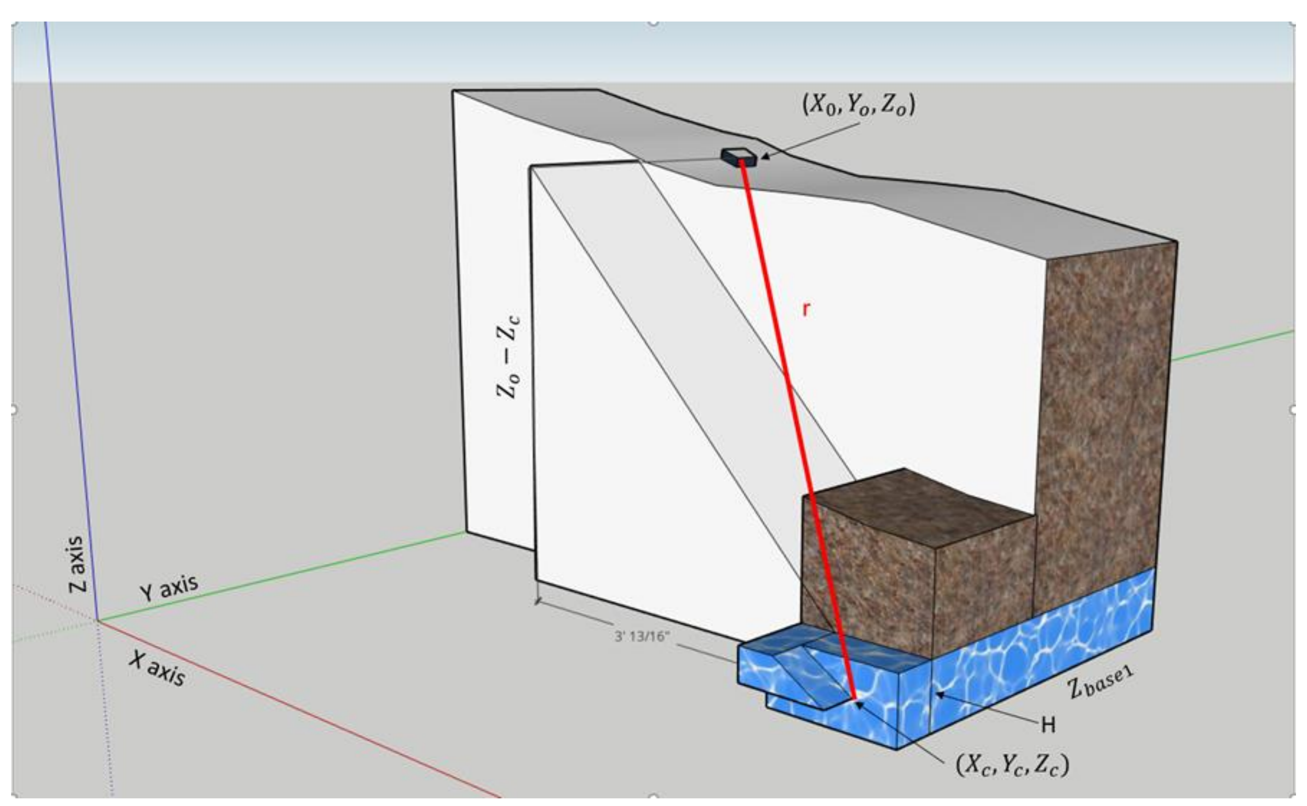

Figure 1: Schematic of distances needed for each cell in a model to calculate the gravity due to that cell within the model

Results

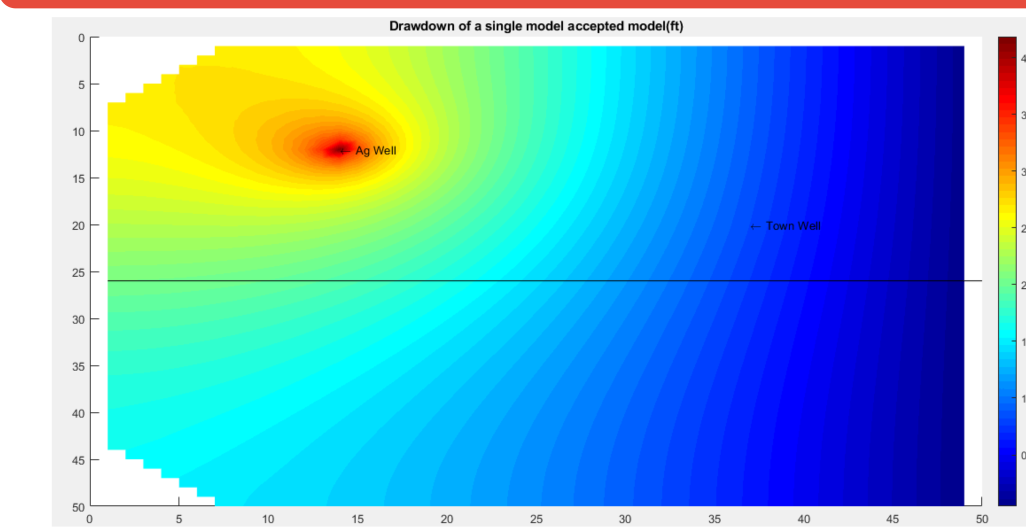

Figure 2: Single Model Drawdown form agricultural well being activated

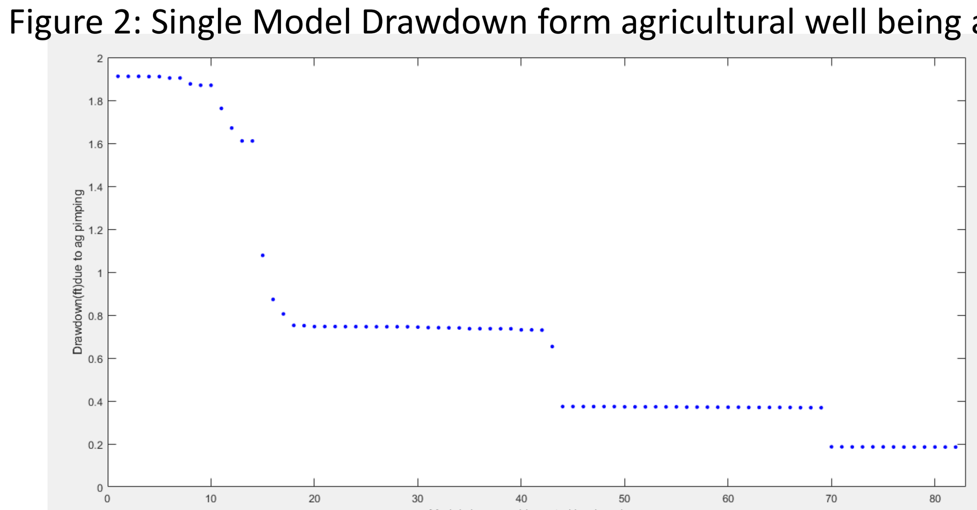

Figure 3: Modeled Drawdown for Ag Well by the 83 models in the ensemble

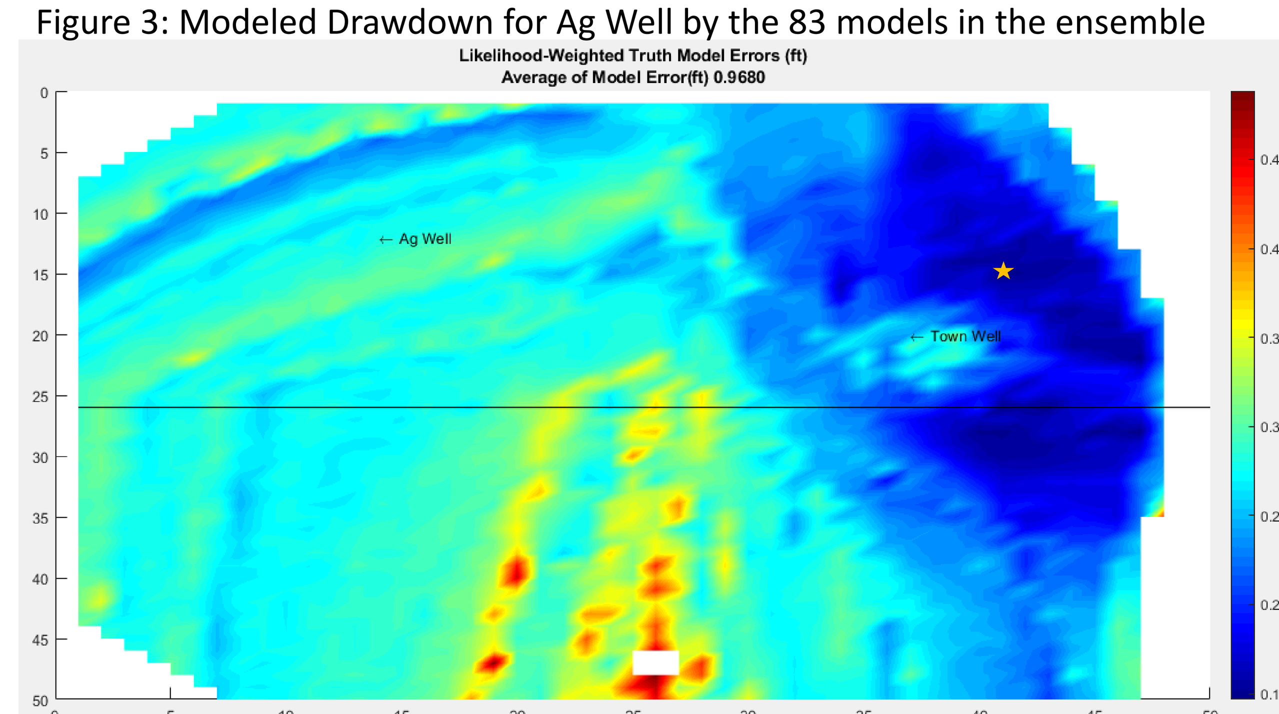

Figure 4: Likelihood weighted error of the forecasted impacts of the ag well on the town well averaged over all models. The gold star represent the location with the lowest average error.

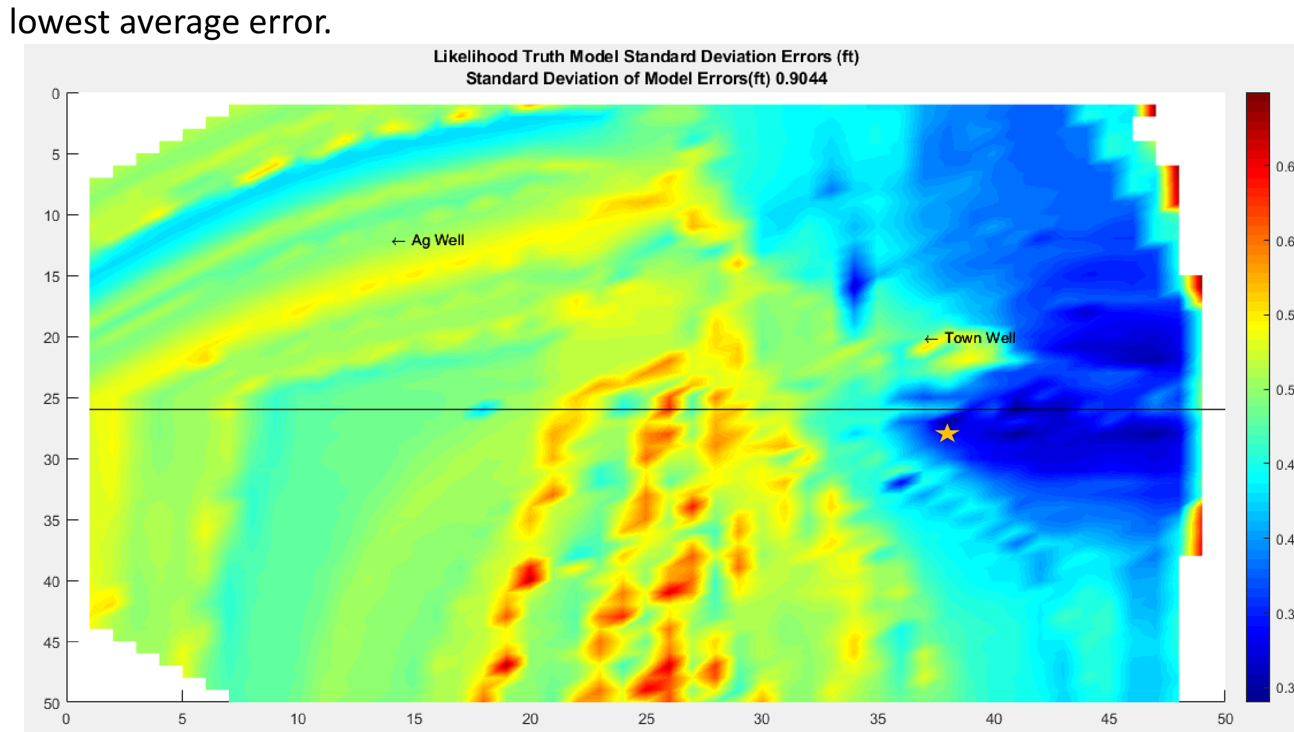

Figure 5: Likelihood weighted standard deviation of the error in the forecast impacts of ag well pumping over all models. The gold star identifies the location with lowest variance over the ensemble..

Discussion

Figure 3, shows the range of forecasted impacts of the ag well on the town well over the model ensemble. Figures 4 and 5 can inform decision makers regarding where to add additional monitoring to reduce their uncertainty regarding the future impacts of an agricultural well on the town well by adjusting the relative likelihoods of the models in the ensemble. There are clear regions where added gravity measurements are most informative either on the basis of reducing the expected error (Figure 4) or on reducing the uncertainty of the expected error (Figure 5). Most of the optimal locations are close to the town well, but on the side opposite of the proposed agricultural well. After adding a gravity measurement, the expected average error reduces from NUMBER to 0.15 ft. However, the lowest variance of drawdown is approximately 0.3 ft.

Conclusions

This method of analysis can be applied to multiple stakeholder groups. Each group could focus on identifying observations that best test the models that result in unacceptable outcomes to them. Each group may identify different optimal locations for additional observations. But, using these maps, they could find locations that offer benefits to all parties, thereby finding compromise early in a groundwater impact investigation.

Future Research

1) Find ways to expand the size of the ensemble to cover more possible conditions while avoiding the proposal of nonbehavioral models;
2) Implement the use of stakeholder utility functions to prioritize the testing of some models within the ensemble to best support decision making in each stakeholder's decision context;
3) Compare the error reduction of gravity versus water level measurements and include this in a cost-benefit analysis of direct (wells) versus indirect (geophysical) monitoring. .

References

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