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Mapping depleting aquifers in drylands and the impact on net primary productivity

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Abstract

The Gravity Recovery and Climate Experiment (GRACE) satellite can measure changes in the height of the water table within 1 cm, unfortunately, GRACE has a horizontal pixel resolution of 40 km X 40 km. We selectively applied a GRACE-based downscaling approach to model the change in the height of groundwater from 2003 to 2017 within distinct groupings of hydrographic basins. We determined that the existence of distinct hydrographic systems at spatial scales smaller than the scale of GRACE pixels does not appear to preclude this downscaling methodology. We then compared this change in the height of the water table over the entire state of Nevada to a net primary productivity (NPP) disturbance map of the frequency of drought on the landscape. We found no significant correlation between disturbance frequency and the modeled change in water table height, implying that aquifer overdraw is not predictive of a reduced ability for the landscape to resist disturbance.

Introduction

Researchers have increasingly turned to NASA's GRACE and GRACE-FO gravimetric missions to address longstanding difficulties in monitoring Earth's groundwater resources. The major limitation of these instruments is the extremely coarse spatial resolution of the data they produce (40-km pixels, Wiese et al, 2016). Numerous research teams have developed methodologies to compensate for this limitation by integrating GRACE data into empirical models alongside finer-resolution climatological and geographic data, that effectively allow for GRACE data to be downscaled to more useful spatial resolutions.

However, many of the most widely-cited GRACE downscaling studies have trained, applied, and validated their empirical models over relatively straightforward topographies (Miro and Famiglietti 2018, Chen et al 2019). There is a need for additional work to refine our understanding of what spatial scales GRACE downscaling methods can be applied and what landscape factors affect the validity of these methods.

The goals of this experiment were:

1. Determine whether GRACE downscaling methods are valid when the study area contains hydrographic basins where no in-situ training or validation method is available.

2. Determine whether trends in downscaled GRACE data correlate with observed anomalies in landscape productivity.

Methods

The study area for this experimentation was the U.S. state of Nevada, chosen because it is 98% Dryland, and its complex basin-and-range topography maximizes the density of distinct hydrographic systems within the footprint of each GRACE pixel. The GRACE downscaling method we utilized for this experiment was a linear regression from least squares (Vishwakarma et al 2021), which was chosen because this experiment was a sensitivity analysis more so than an attempt to maximize model accuracy. The modeled variable was the flux of the height of the water table, with the interannual period resetting in March rather than January due to the greater availability of in-situ well measurements. March is also the beginning of the growing season for Nevada's primary dryland crops.

The in-situ data for this experiment were compiled from records maintained by the Nevada Division of Water Resources (NDWR 2024). The majority of these records were drawn from private agricultural and industrial users, with great variation in the quality and consistency of record-keeping. Because of the inconsistencies within these data, we applied GRACE downscaling to the overall trend of the water table from 2003 to 2017 rather than to an interannual time series. Applying GRACE downscaling methods at decadal rather than interannual timescales has some precedent in the literature (Scanlon et al, 2018).

We addressed our first research goal by utilizing two different methods of organizing training/validation data from in-situ records. We also leveraged the set of hydrographic basins delineated by past surveys (USGS, 1971). To produce our first dataset, we simply withheld 20% of the available site records for validation purposes, and otherwise used the available training data irrespective of location or site type. We refer to this as **the basin-inclusive method**.

To produce our second dataset, we chose a subset of hydrographic basins from within the study area and used in-situ records from these as training data. We then chose a second subset of hydrographic basins from within the study area to use as validation data. These basins were non-contiguous, meaning that the validation data were both spatially and hydrographically discontinuous from the training data. We refer to this as **the basin-exclusive method**.

The two methods cannot be directly compared because of the differing distribution and amount of training and validation data available in each case. However, we reasoned that if the second training/validation approach produces a respectable accuracy, we may have some confidence that the aquitards between hydrographic basin do not invalidate GRACE downscaling approaches applied over areas that contain multiple distinct hydrographic systems.

We addressed our second research goal by applying our downscaling approach to the entire State of Nevada and then compared this to a raster representation of the frequency of drought disturbance on vegetation in the landscape. This raster represented drought "disturbances" as events where the annual net primary productivity NPP (Robinson et al, 2019) decreased 20% or more relative to the time-series mean. We reasoned that since most of Nevada's waterways are groundwater-dependent, consistent aquifer overdraw may be reflected in the landscape's resilience to disturbance. We tested this hypothesis by testing for spatial correlation between this disturbance frequency and the modeled change in water table height.

Results

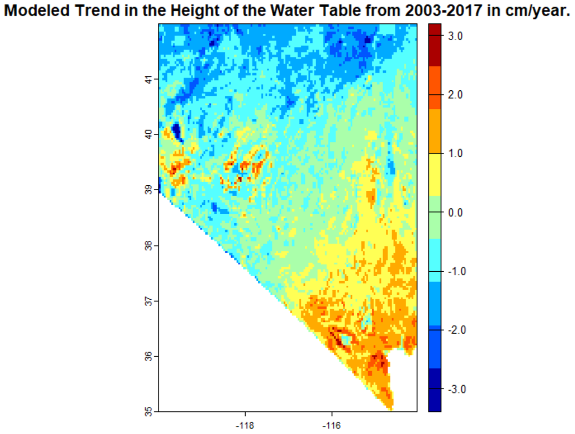

Figure 1: The state of Nevada model output based on the basin-inclusive training/validation dataset. The set of predictor variables include the flux in precipitation (mm), the flux in mean annual temperature (*C), the soil water content at field capacity at 200 cm depth, the soil bulk density (kg/m^3) at 200 cm depth, and elevation (m). These variables were retrieved via Google Earth Engine (Earth Engine Data Catalog, 2024). The target resolution for this method was the 4km resolution of the PRISM precipitation dataset (Daly et al, 2008). This model had a RMSE of 2.8 cm/year and a normalized RMSE of 0.15.

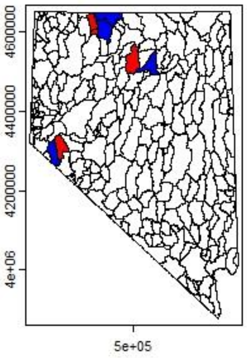

Figure 2: The basins chosen for the first, basin-selective training/validation dataset. Basins in blue contained points used for training, basins in red contained points used for validation. The model was trained using the basin-exclusive training/validation dataset and had a RMSE of 1.8 cm/year and a normalized RMSE of 0.15, indicating that the model is somewhat less reliable than the one produced using the basin-inclusive data.

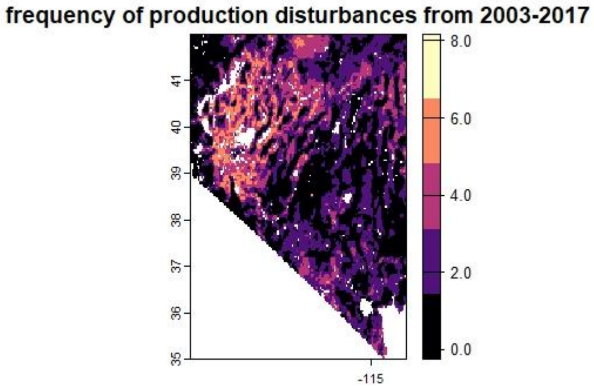

Figure 3: The drought disturbance net primary productivity (NPP) frequency raster was used to test whether there was an observable relationship between the GRACE modeled change in the water table height and the resilience of groundwater-dependent ecosystems. We observed no significant spatial correlation between these variables (*p* = 0.17).

Discussion

These experiments revealed a considerable need for further investigation. The basin-exclusion method for investigating the effects of aquitards on the downscaling methodology shows promise, but could be refined by more carefully curating the excluded basins to control for underlying geology and dominant land-use type.

The lack of correlation between groundwater levels and disturbance frequency could have several causes, and likewise indicates a need for more refined investigation. This could indicate that the groundwater model performs unreliably in areas between or far away from training/validation points, or the correlation could be thrown off by the behavior of agricultural water users, who account for a majority of groundwater usage and may be maintaining artificial "islands" of stable landscape production at the cost of aquifer overdraw. Controlling for land use in future iterations of this experiment should allow us to isolate which of these explanations is more likely.

Acknowledgements

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