Estimating the variability in long-term sustainable groundwater elevations for a moderate-altitude rain-fed groundwater basin under a drying climate

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Abstract

Climate change is expected to exacerbate the severity of winter storms and the length of droughts in semi-arid regions such as California. Moderate altitude (mid-mountain) groundwater basins in these regions are dominantly rain-fed with little snowmelt, that will disappear with climate change, which makes natural recharge essential to maintaining agricultural, domestic and ecosystem water needs. Butte Valley resides in one of these basins and due to its high natural recharge it was not considered cost effective to connect it to a major water project to fulfill agricultural needs, and in this era it would be even more expensive to develop water imports. Thus, the future of moderate altitude agricultural basins are at risk due to climate change if the geologic structure does not benefit the retention of groundwater storage for later groundwater pumping. Here we apply a groundwater flow model of the Butte Groundwater Basin under a standard 2030 and 2070 wet and dry climate scenarios to investigate whether long term sustainable groundwater levels can be achieved. Under climate change these moderate altitude basins may prove essential to continued agricultural production as they see slower warming if they can maintain sufficient available groundwater for agricultural production.

Introduction

Increases in population growth, economic development and agriculture in semi-arid areas has led to high rates of aquifer depletion worldwide (Bierkens and Wada 2019). Groundwater dependent irrigated basins worldwide are at risk of depletion due to climate variability increasing the severity of droughts reducing surface water available (Taylor et al. 2012). The mountain regions of western North America have seen a decrease in spring snow accumulation due to rising temperatures which has removed the natural water reservoir many western states are dependent (Cayan et al. 2005). In addition to this lack of snowpack, there is an expected increase in precipitation volatility leading to more volatility in surface water flows which reduces their availability for irrigation due to the lack of reservoir and canal capacity (Swain et al. 2018).

Moderate-altitude basins such as Butte Valley, approximately 4,000 ft AMSL, are highly dependent on large winter storm rainfall events to replenish the groundwater basin through dispersed natural vegetation recharge. Although moderate-altitude basins don't have the same magnitude of productivity as semi-arid valleys, they can be quite agriculturally productive which due to a positioning in the mountains have limited surface water flows and reservoirs. Therefore, moderately high-altitude basins such as Butte Valley are almost wholly dependent on groundwater pumping for agricultural and domestic water uses.

As the effects of climate change continue to exacerbate the severity of droughts and winter storms in semi-arid regions, will moderately high-altitude basins find a long-term sustainable groundwater yield in a drier climate with less natural recharge and a higher dependence on groundwater.

Researchers frequently apply groundwater flow models and apply climate change scenarios to investigate the potential long-term effects of varying climate on groundwater storage and use. Butte Valley is unique due to its complex volcanic geology, and that little study has been done on moderate altitude groundwater basins entirely dependent on natural recharge for groundwater withdrawal because it was decided in the 1980s that it was not worth the cost to connect the basin to a Bureau of Reclamation project (*Butte Valley Division Klamath Project Concluding Report* 1981). Thus it is critical that there is consistency in the natural recharge to balance groundwater pumping, but with the expected increase in severe winter storms and longer droughts, it is uncertain whether the recharge in wet years will be sufficient to offset droughts in the long term.

Objective

The main objective of this project to develop a groundwater flow model to accurately depict the recent groundwater history of Butte Valley to understand the system dynamics dependent on alluvium and quaternary volcanics. Additionally, from 1990-2018 there has been a shift in the natural recharge due to climate change which will may have a large impact on groundwater levels as upland precipitation is the dominant recharge source. The groundwater flow model will be extended to 2030 and 2070 to further investigate the impacts of climate change on groundwater storage and availability for use.

Project Tasks

1. Develop a transient groundwater flow model of Butte Valley to develop a historical water budget from 1990-2018 and calibrate the groundwater flow model with historical groundwater elevation measurements
2. Alter the input from the historical model to project forward the model to create 2030 and 2070 climate change projections based on DWR expected water year types
3. Summarize the outputs of the groundwater flow models as annual water budgets to look at the trend in groundwater storage change
4. Compare the expected 2030 and 2070 mean groundwater elevations to the depth of the wells in the basin to determine whether groundwater pumping will be sustainable

Hypothesis

Given that Butte Valley is highly dependent on a recharge source that will become increasingly unpredictable with climate change I would expect to see high interannual variability of net change in groundwater storage which a long-term downward trend if pumping is held constant. The California Department of Water Resources has water year type predictions to the year 2030 and 2070 under dry and wet climate conditions that scale the amount of expected precipitation and evapotranspiration in a given year. These climate scenarios will be applied to the Butte Valley groundwater model to determine whether the basin will reach sustainable groundwater levels under the dry climate scenario and under what timescale it takes to reach a new equilibrium.

Data Sources

- **DWR geologic report 1960** (Wood 1960)
- **DWR regional geologic maps** (Jennings 1977)

- **DWR periodic groundwater elevation data** (*Periodic Groundwater Level Measurements* 2021)
- **Larry Walker and Associates groundwater elevation database for Butte Valley**
- **David's Engineering soil water budget modeling data prepared for Larry Walker and Associates** (*Butte Valley IDC Water Budget Estimates, unpublished report* 2020)
- **USGS MODFLOW and PRMS models of the Klamath River region** (Gannett et al. 2012)

Methods and Assumption

1. MODFLOW

a. Import geology into MODFLOW model which was developed by Bill Rice using regional geologic maps hosted by DWR and local geologic reports (Wood 1960)

b. Apply horizontal outflow boundary conditions based on historical groundwater trends that show groundwater outflow from Butte Valley to the Klamath River to the north and to Tule and Klamath Lake to the east (Gannett et al. 2007)

c. Apply recharge and groundwater pumping to the groundwater flow model based on the David's Engineering IDC report for irrigated lands and based on the USGS PRMS model for the native vegetation (*Butte Valley IDC Water Budget Estimates, unpublished report* 2020; Gannett et al. 2012)

2. UCODE

a. Run the groundwater flow model for a steady state period based on an average of the first 10 year period of groundwater recharge and pumping while comparing the simulated groundwater heads to an average of the observed water elevations for each observation well

    i. UCODE will alter the hydraulic conductivities specified iteratively to attempt to best match the observed heads with simulated heads

b. Run the transient groundwater flow model from 1990-2018 while comparing the simulated groundwater heads to the observed water elevations for each observation well

    i. The hydraulic conductivities are already mostly accurate based on the steady state calibration, but will still be allowed to vary to get more precise values

    ii. UCODE will alter the storativities specified iteratively to attempt to best match the observed heads with simulated heads

iii. Due to a limitation of groundwater observations only in the alluvial aquifer, we are limited by how precisely we can calibrate the volcanic aquifer which is acceptable given the future projections will be a comparison to a baseline

3. Future Projection

a. The DWR has specified corresponding water year types if a historical year occurred in a future scenario going to 2030 or 2070 under varying climate scenarios

b. The historical groundwater flow model will be repeated several times with scaling factors determined by DWR to implement what recharge and evapotranspiration might look like under wetter and drier future climates

4. Water Budgets

a. The projected groundwater inflows and outflows to the basin will be summarized to an annual basis to look at the change in groundwater storage over time to determine whether there is a sustainable groundwater yield

b. The projected groundwater levels will be compared to the depth of the wells in the basin to determine whether any wells will go dry in the basin under future climates

Results and Discussion

The groundwater flow model described in the methods section was simulated under five future climate change scenarios: base, 2030, 2070, 2070DEW and 2070WMW. These scenarios represent a range in future climates with varying increases and decreases in precipitation and evapotranspiration depending whether the future climate is expected to become drier or wetter.

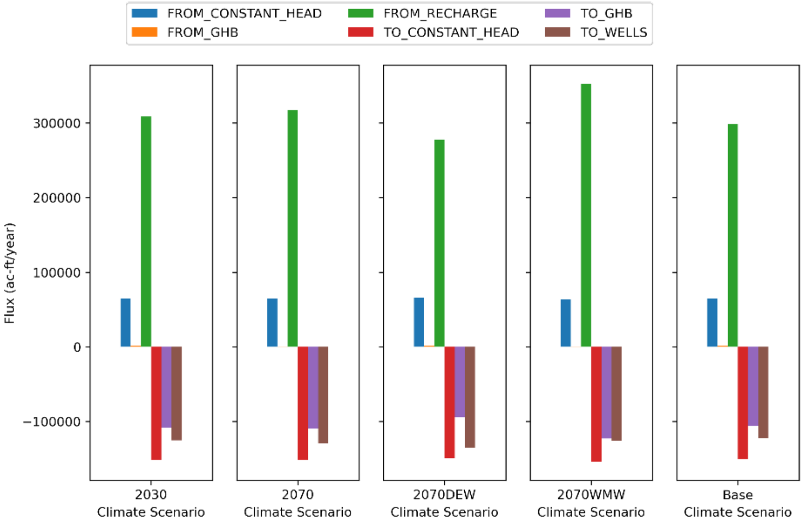

Figure 1: The annual water budgets for each climate scenario were averaged over the 1990-2070 period to demonstrate the differences in recharge and pumping between the scenarios.

Under all climate scenarios the average groundwater pumping increased, with the dry scenario increasing pumping the most, and only the dry scenario decreased recharge while all other scenarios increased recharge.

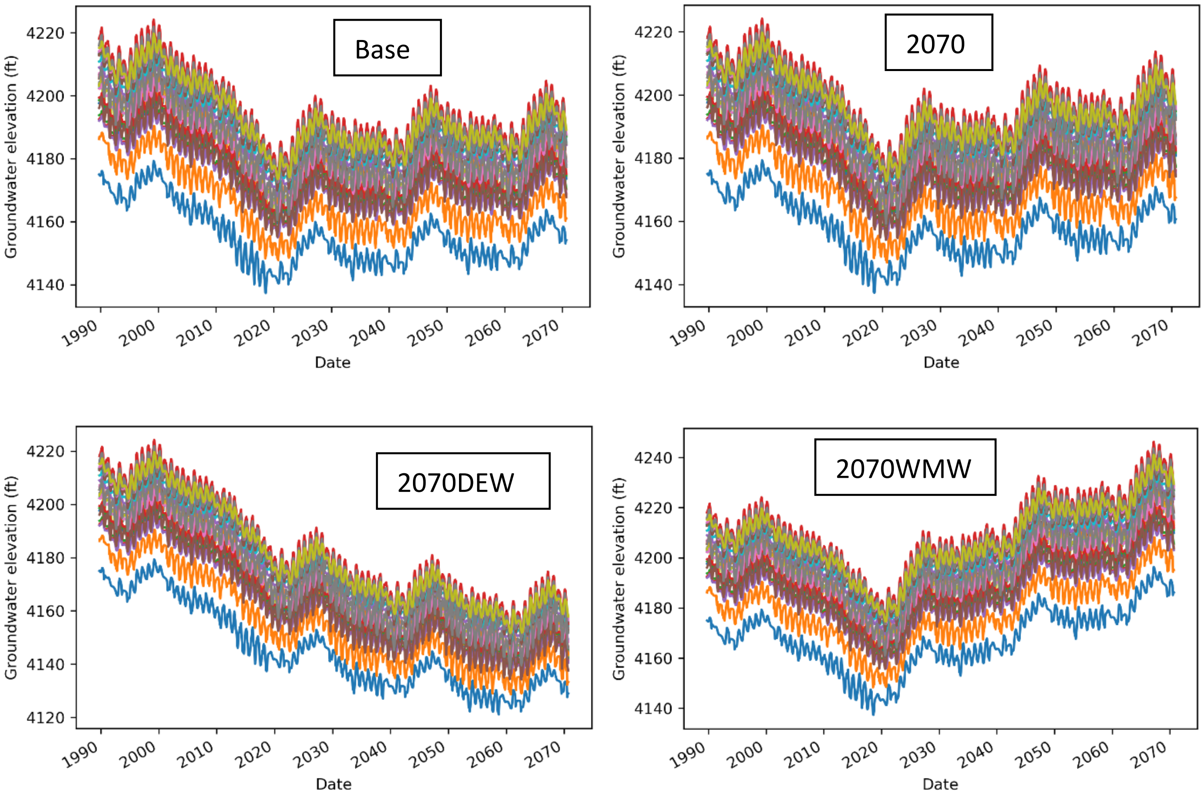

Figure 3: Simulated head time series from 1990-2018 (historical model) and 2019-2070 (climate model) with climate change factors applied to previous model years that will represent a future year, e.g. 1997 was a

moderately wet year thus if 2035 should be a moderately wet year then the climate for 1997 can be applied in 2035 after being multiplied by a change factor to account for the climate scenario.

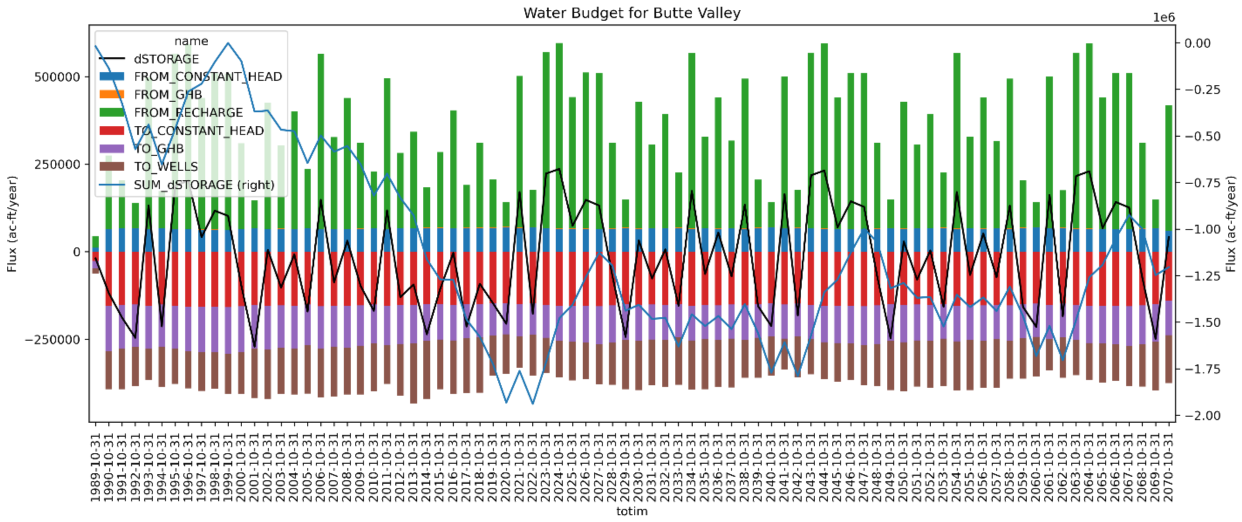

Figure 4: All of the water budgets for the future climate scenarios have similar dynamics to the Base climate scenario as they are all based on the same water year typing and future matching. The major difference will be the magnitude of inflows and outflows from the model domain which are clearly summarized by looking at the cumulative change in storage between the scenarios.

The sum of storage for the year 2070 is as follows for the climate scenarios:

Base: -1.2e6 ac-ft, 2070: -0.7e6 ac-ft, 2070DEW: -2.7e6 ac-ft, 2070WMW: 1.1e6 ac-ft

Thus for all climate scenarios except the wet future climate there is a net loss in groundwater storage, however, it is necessary to review the simulated head time series to understand the majority of the loss in storage is from the years 2000-2020 while the following years of simulated climate tend to recharge the storage due to the reoccurrence of the 1996-2000 wet years. Although the sum of storage values do not show it yet, the trend in water levels for the Base, 2030, 2070 and 2070WMW suggest that eventually all of these scenarios should recover any loss in groundwater storage. The 2070DEW scenario suggests a continued lowering of groundwater levels which will decrease groundwater storage until the heads are lowered such that subsurface outflow decreases allowing for an equilibrium of pumping and recharge.

Conclusions

The general trend of the climate change groundwater model results indicate that future groundwater pumping may maintain the current conditions because the expected recharge will continue to offset any pumping while increasing storage. Beyond the offset of pumping with recharge, the critical factor under a drying climate is quantifying the volumes of subsurface discharge to adjacent groundwater basins or surface water bodies. Although under future climate it appears the recharge in the Butte area will offset pumping this does not prove that the subsurface flows will remain at there same magnitude, potentially negatively impacting neighboring basins reliant on subsurface inflow for groundwater recharge. Ultimately the success of groundwater flow models in depicting future climate depends on a proper representation of the subsurface especially when hydraulic gradients can be severe due to the altitude of the basin, the accuracy of hydraulic conductivity can have a major influence on projected subsurface flows.

Recommendation and Limitations

The current application of DWR climate change factors indicates that the Butte Valley area will not see a severe decline of groundwater levels, but in fact will see a rise in groundwater levels and storage. Based on these modeled results, the Butte Valley area will not need to make any major changes in future groundwater use if the expected future climate falls between the 2030 to 2070WMW climate scenario. If the future climate in reality is closer to the 2070DEW scenario then groundwater use will need to be reduced if it is desired to prevent a lowering of greater than 5 m based on the 2015 groundwater conditions, the current draft Sustainable Management Criteria. To prepare for the reality that future climate may be drier, the groundwater sustainability plan should determine the importance of different crops grown in the basin and consider the introduction of domestic water conservation measures as a final option.

An important caveat to the presented results is that all of these climate change scenarios were based on water year relations using the modeled period from 1991-2011 which has a strong impact on model results because 1996-2000 was a period of very wet years that result in uncommonly large recharge. Thus future models should vary the water years included into the future climate to more realistically capture the variation between wet and dry years for the scenario that there are not frequently occurring wet periods.

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Appendix

Groundwater model calibration results and calibrated hydraulic parameters.

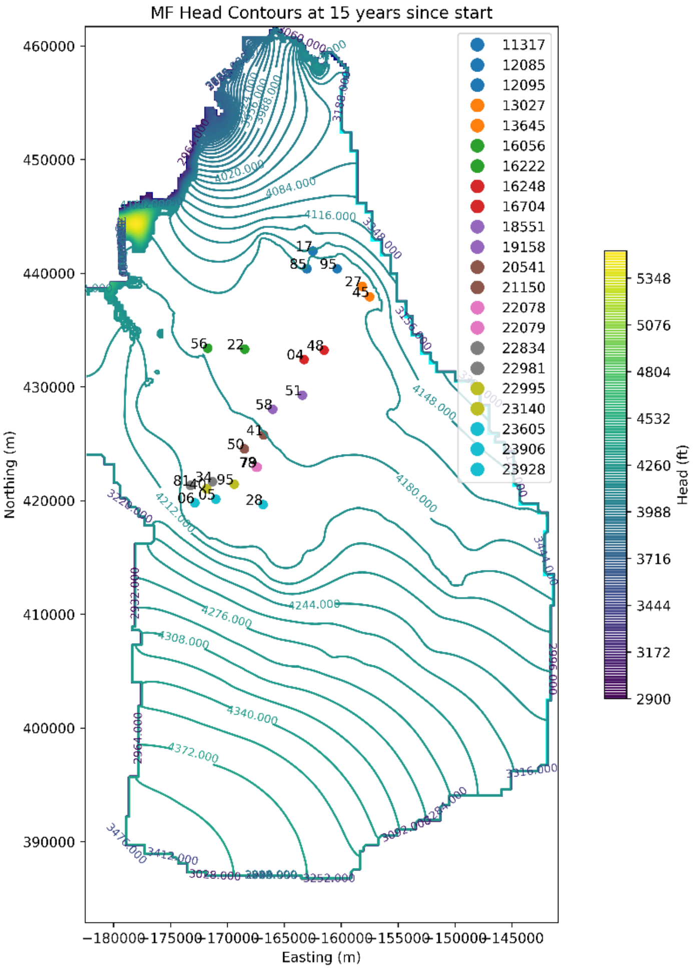

Figure S1: Modeled heads 15 years after model initiation and the location of nodes with observation well data.

Table S1: Final hydraulic parameters after model calibration

Lithology	Zone	Kx	Ky	Kz	Ss	Sy
Qb	2	1.80E+00			1.00E-03	0
Qtb	4	1.8			1.00E-03	0.01
Sediment	6	670			1.00E-04	0.1
Tvw	7	0.05545			1.00E-03	0

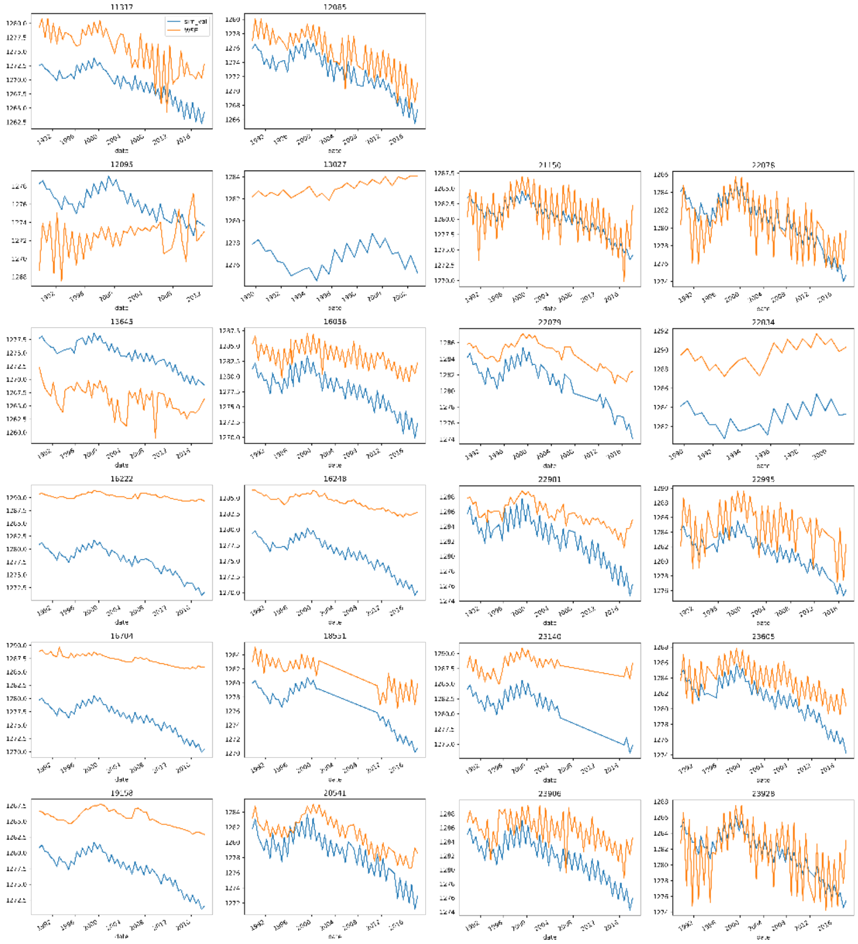

Figure S2: Time series of simulated (blue) vs observed (orange) heads for observation wells with more than 10 observations as seen in the map above. The system dynamics are matched well between the majority of the wells and the difference in head is comparable to previous groundwater models in the region. Additionally, those observation wells with poor match indicate that the observation well may be