Developing a Framework for Estimating Groundwater Connections to Wyoming Reservoirs

Final Report

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Abstract

Wetland protection is a major concern for managing, expanding, and building reservoirs in Wyoming. An important factor in wetland resilience near reservoirs is the availability of water to wetland ecosystems across a range of reservoir water levels that are dictated by water needs downstream as well as the overall water availability for a given year. The purpose of this study was to investigate how groundwater may serve as a potential buffer for reservoir water storage and reservoir-related wetlands by reducing water stresses during low or variable reservoir conditions. A framework for monitoring and predicting the hydrologic connection between reservoirs and surrounding groundwater systems was developed, combining field-based analysis and groundwater flow simulations. An outcome of this project is a Python-based implementation of MODFLOW for groundwater-reservoir interactions that can be used to predict groundwater levels near specific Wyoming reservoirs with minimal input datasets. Reservoir management strategies that maintain groundwater levels near the land surface despite low reservoir levels may allow wetland sustainability while providing maximal water to downstream users. The field study served as a natural experiment to understand how water tables respond to changing reservoir conditions, and it also created an example dataset that can be emulated for other reservoirs to enhance model prediction accuracy and future reservoir management. In ongoing work, the validity and accuracy of the model will be tested and improved by the groundwater monitoring data.

Project progress

Objectives

Given the large number of both reservoirs and reservoir-related wetlands in Wyoming, a flexible framework is needed for quantifying how reservoir water levels may affect the annual water budget of a reservoir, as well as wetland health. First, the hydrologic feedbacks between reservoir management and adjacent groundwater conditions are poorly understood. As reservoir levels fall to supply water to stakeholders across the state or during drought, groundwater may provide a secondary water storage and delivery system that could support wetlands surrounding reservoirs to comply with federal wetland regulations. This slow seepage of reservoir water that infiltrated into nearby aquifers during high water levels (i.e., bank storage) may support sufficiently high water tables to maintain some groundwater return flows and wetland water needs, even during low reservoir levels (Rains et al., 2004). The degree to which groundwater surrounding reservoirs can discharge back into the reservoir during low stands is unknown and will change depending on the hydrologic, geologic, and climatic conditions for each of reservoir in Wyoming. Thus, the combination of field data and a flexible modeling tool that incorporates these site-specific data would contribute to maximizing individual reservoir management strategies while protecting wetlands.

Two questions motivated this study on the connection between reservoirs and groundwater systems:

1) Under what hydrogeologic conditions do reservoir levels impact surrounding groundwater systems and dependent ecosystems? and

2) How do reservoir management decisions affect local groundwater levels and fluxes?

Reservoirs in Wyoming are located in areas with diverse geologic, topographic, and hydrologic conditions that lead to unique reservoir-groundwater interactions. Thus, an objective of this study was to create a flexible framework with an underlying groundwater model that can receive site-specific information ranging from geology to anticipated water needs in the future. Then, using this groundwater model, the effects of reservoir level changes in combination with future climate conditions on groundwater levels can be tested. Specifically, the depth of the water table beneath the land surface can be forecast for a wide range of reservoir level scenarios. Locations where both reservoir and groundwater levels are below the rooting depth of wetlands would indicate management and climatic feedbacks that result in high risk for wetland water stress.

An important component of the testing the modeling framework was to develop and implement a groundwater monitoring field study around a reservoir to both inform and calibrate groundwater models and provide independent hydrologic results without relying on groundwater modeling. To achieve this, the Wyoming Hereford Ranch Reservoir 2 (WYHRR2) was chosen for installing monitoring wells instrumented with groundwater level sensors along with other hydrologic measurements. These data provided real-world observations into the hydrologic connection between wetland groundwater and reservoir levels and inform the development and calibration of the groundwater model. The field data collection can serve as an example for reservoir managers to develop their own monitoring networks that can inform their applications of the groundwater modeling.

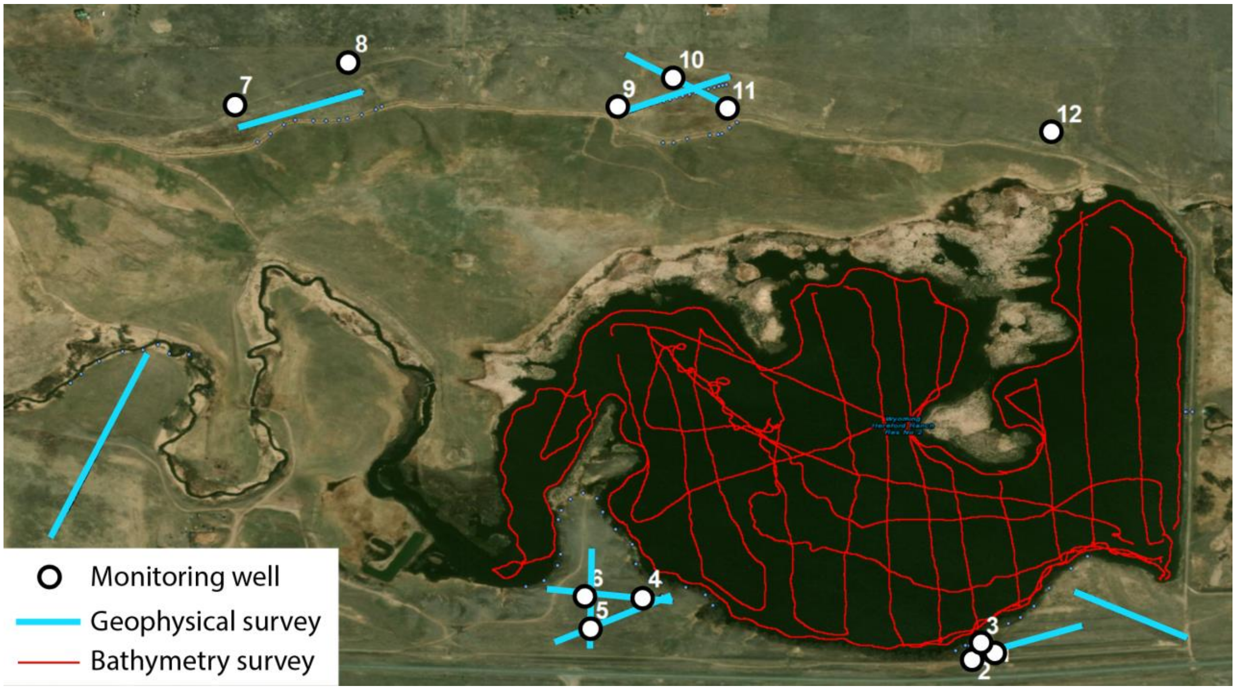

Figure 1. Overview of field data collected at WYHRR2.

Methodology

Field observations at WYHRR2

After consulting with the Wyoming State Engineer’s Office, we chose and obtained permission to conduct the groundwater monitoring for this project around WYHRR2 (Figure 1). WYHRR2 is a dammed portion of Crow Creek and has a ~0.5 km^2 area at high stage. Seasonal monitoring of the water levels in WYHRR2 over two of the project years measured a range in reservoir stage of ~2 m with the peak occurring during the Spring and likely related to seasonal snowmelt supplied by the headwaters in the Laramie Range.

During high water levels in the late Spring 2018, we conducted a bathymetric survey of WYHRR2 with a sonar system owned by the University of Wyoming. This sonar mapping was used to create a bathymetric raster that was merged into a digital elevation model that included both bathymetry and topography (Figure 2a). This data product is useful as an input into the groundwater flow modeling as well as independently to calculate the stage-storage relationship for the reservoir (Figure 2b).

In Summer 2018, we drilled 14 wells while also saving the recovered sediment cores for later analyses. A GeoProbe system and operators were hired from the Wyoming Center for Environmental Hydrology and Geophysics (WYCEHG) at UW to perform the well drilling. In addition to these cored wells, we installed three shallow wells near the reservoir, of which one remained sufficiently saturated to use for the long-term monitoring project. Since the GeoProbe was used to core for the drilling, only unconsolidated sediment could be recovered, and the well depths were limited to no more than 10 ft below the water table during the drilling, as the borehole walls would rapidly collapse below the water table. These limitations and the somewhat higher water table during the drilling led to several of the wells going dry during the monitoring program (Figure 3). In each viable well, 2 in diameter PVC tubing was installed as the well casing, with the lowermost 10 ft of each well fully screened and open to groundwater fluctuations. All of the wells were installed into the unconfined groundwater system surrounding WYHRR2, and several of the wells were drilled until refusal, which we interpreted to be a more cemented sandstone on which is also the foundation for the WYHRR2 dam. Several hundred feet of core was recovered from the wells. The core was analyzed noninvasively using a Geotek Multi-Sensor Core Logger housed in the Department of Geology and Geophysics at UW. Portions of the core were also used to perform over 200 measurements of saturated and unsaturated hydraulic properties using Meter KSAT and Hyprop lab equipment in the Befus Research Lab. Field-based measurements of saturated hydraulic conductivity were performed at select locations using a Meter Saturo system. These measurements of hydraulic conductivity and porosity are being used in the ongoing development of the WYHRR2 groundwater model that is extending beyond the end of the project funding.

The water levels in 12 of the wells were recorded every 30 minutes with water level and temperature loggers for nearly two years (Figure 1). Manual measurements of the water levels in the monitoring wells were performed roughly four times a year to correct for drift in the sensors, as well as to download the data and to check on disturbances at the site (e.g., cattle pulling out sensors). Two barometric pressure loggers were also installed at WYHRR2 to correct for changes in atmospheric pressure in the well loggers measuring total pressure.

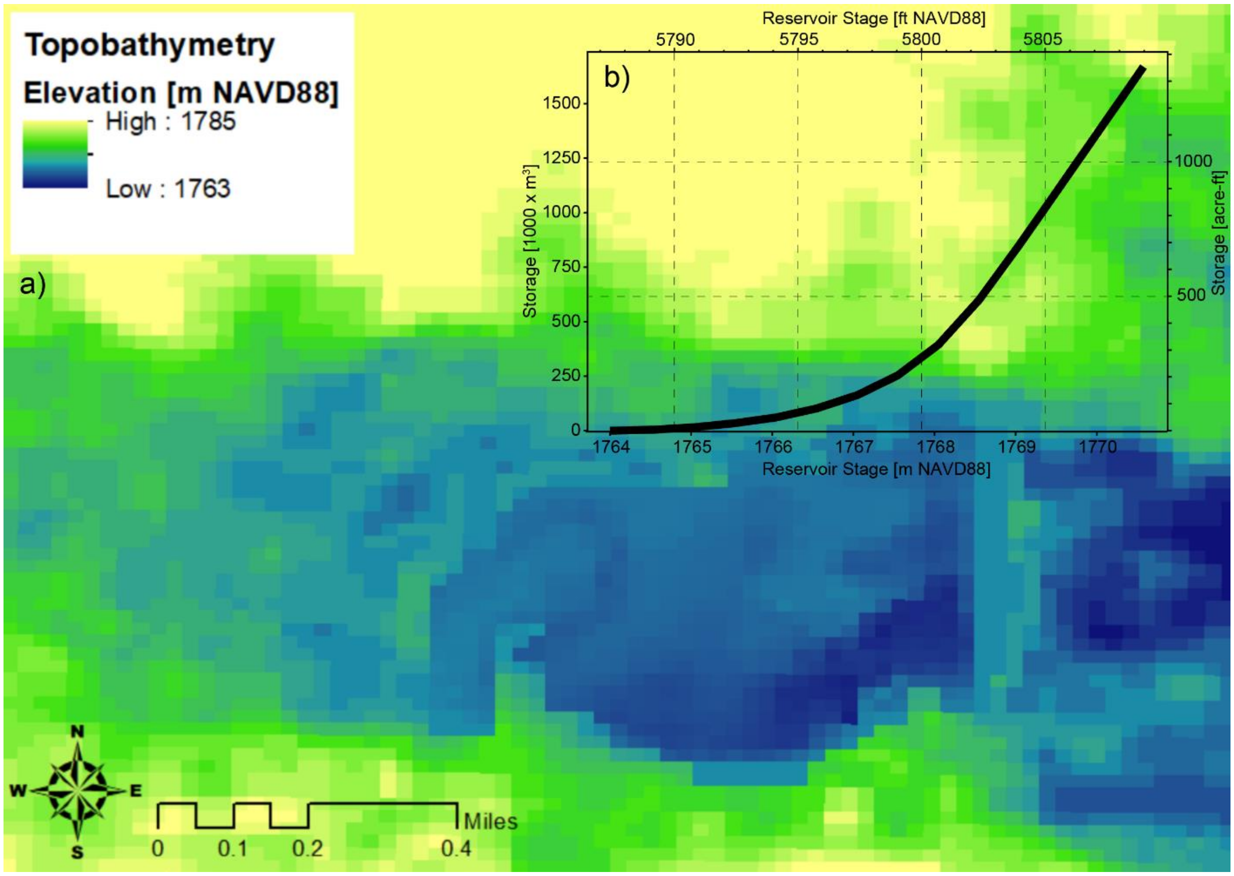

Figure 2. a) Topobathymetry dataset produced in this project for WYHRR2, and b) the stage-storage relationship calculated from the bathymetry mapping.

Shallow electrical resistivity tomography and seismic refraction surveys were performed in Summer 2019 to image the hydrogeologic structure and material properties of the subsurface, including a snapshot of the position of the water table. Nine survey lines of each method were collected and are in the process of being used to construct a three-dimensional hydrogeologic framework for the WYHRR2 study area.

With the project ending in 2020, we removed the monitoring equipment and wells. The boreholes were filled with sand until ~5 ft from the ground surface with the remaining sealed with bentonite. We offered to keep the well installations and loggers for either the Wyoming State Engineer's Office or other faculty at the University of Wyoming, but no one was available to maintain the monitoring system after K. Befus moved to his new institution.

Numerical modeling framework

Two numerical modeling approaches were developed as part of this project, both using MODFLOW as the underlying software for solving the groundwater flow problem controlled using Python scripts (Bakker et al., 2016; Harbaugh, 2005). The first modeling framework used generic two-dimensional model geometries to investigate how various hydrogeology and topography influence a groundwater flow system connected to a reservoir (Figure 3). This simple framework was only for groundwater flow perpendicular to the shoreline of a reservoir, and it did not account for three-dimensional effects. This analysis build from previous work on the development of a seepage face in topographic lows in the absence of surface waterbodies (Bresciani et al., 2016). The simplicity of this approach allowed us to run several tens of thousands of the models to investigate the development of seepage faces adjacent to reservoirs with varying water levels.

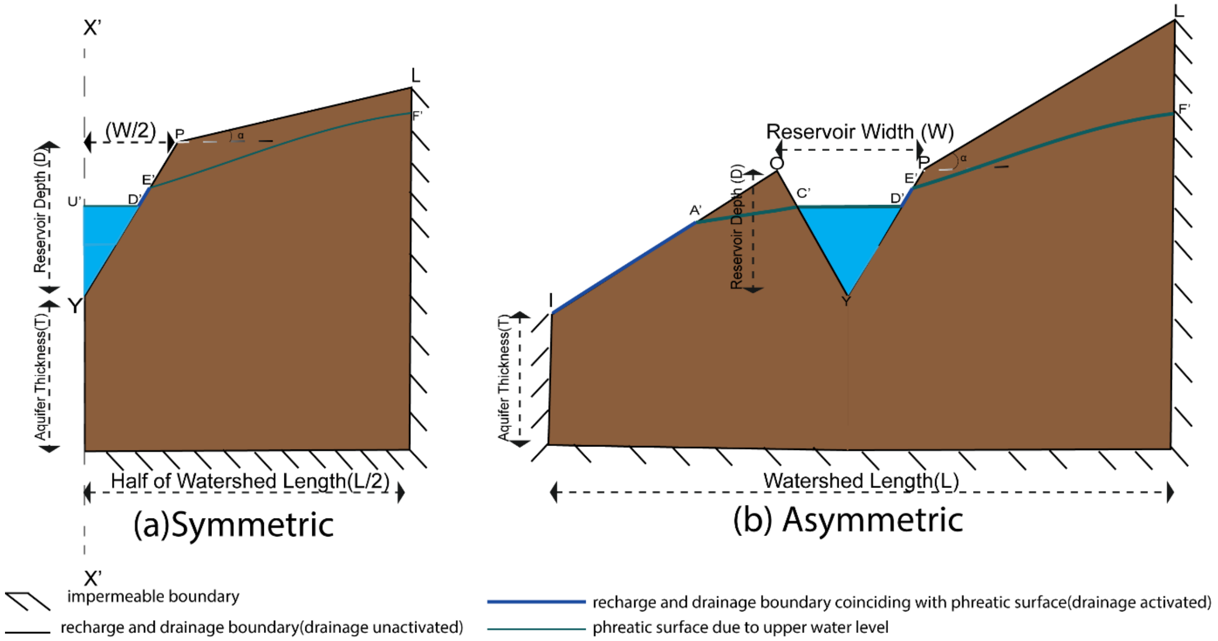

Figure 3. Generic reservoir-groundwater system model framework.

We also developed a framework for more complex groundwater-reservoir interaction modeling that could ingest site-specific datasets on the hydrogeology, climatology, topography, and reservoir stages. The modeling framework was also developed in Python using FloPy (Bakker et al., 2016) as well as several other Python packages (e.g., GeoPandas, Rasterio, Matplotlib, and NumPy). The groundwater model can be constructed in two (i.e., map-view) or three dimensions, depending on the amount of information available about the hydrogeology of a site. The code and example scripts for running it are available on https://github.com/kbefus/wy_gwres, along with the field datasets collected as part of this research. We will continue to work on finalizing this portion of the project over the course of the next year, and we will update the repository with these changes.

Principal findings

With the fieldwork and observations collected at WYHRR2, we found that the reservoir is primarily serving as a discharge location for groundwater for most of the year. This was deduced from the water level in the reservoir being consistently below the water table to the north and south, and the hydraulic gradients calculated from the monitoring well observations also indicated groundwater flow into WYHRR2 (Figure 4). We are in the process of validating the reservoir water level observations with sporadic water level measurements we took, and this could lead to a new relationship between the groundwater levels and the reservoir. From the monitoring well observations, the water table to the south of WYHRR2 are very responsive to changes in the reservoir water level. The filling of the reservoir in Spring 2019 by ~0.5 m caused water tables on the south side of the reservoir to rise by ~2 m. This magnification of the reservoir stage gain is likely caused by the combination of the rise in the reservoir level as well as a melt-related diffuse recharge pulse to the aquifer. Such a response would suggest that groundwater flows from the south into the reservoir, in addition to the preliminary relationship of the observed heads (Figure 4). The northern monitoring wells were less responsive to changes in the reservoir level, although a seasonal change of ~1 m in water table elevation was observed. Additional analysis will test the effect of interannual reservoir levels on the water table elevations, as well as the large change in reservoir water levels in 2019 that may be related to a change in management or could be an artifact of changing the sensor location. We have not yet acquired reservoir levels for 2020 from the State Engineer's Office.

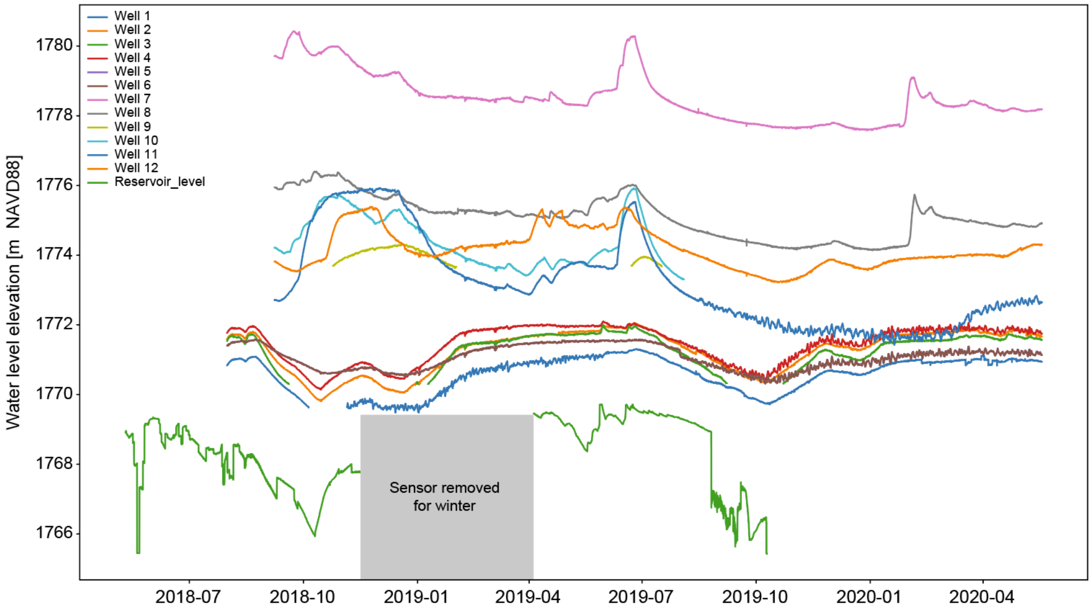

Figure 4. Groundwater monitoring observations for the WYHRR2 over the course of the project with the reservoir level observations from the WY State Engineer's Office. Gaps in the time series for each well indicate when the water table was lower than the monitoring well screen. Noisy data towards the end of the monitoring period are being investigated and could be related to either clogging of the sensor with mud or the need for additional barometric corrections.

The geophysical surveys provided very useful information for constraining the water table position at the time of the surveys and for delineating the thickness of the unconfined aquifer (Figure 5). The seismic refraction surveys highlight the change in density between the overlying sand aquifer and a more consolidated sandstone. We will compile the depth of this contact from both the seismic surveys and the drilling logs and use this depth in the numerical modeling to set the lower base of the unconfined aquifer. The electrical resistivity surveys similarly contain useful information for constraining the elevation of the bedrock contact, represented as an increase in resistivity at depth. The water table positions from the electrical resistivity surveys will also be used to validate the numerical groundwater flow modeling, although this validation dataset will be secondary to the monitoring well observations.

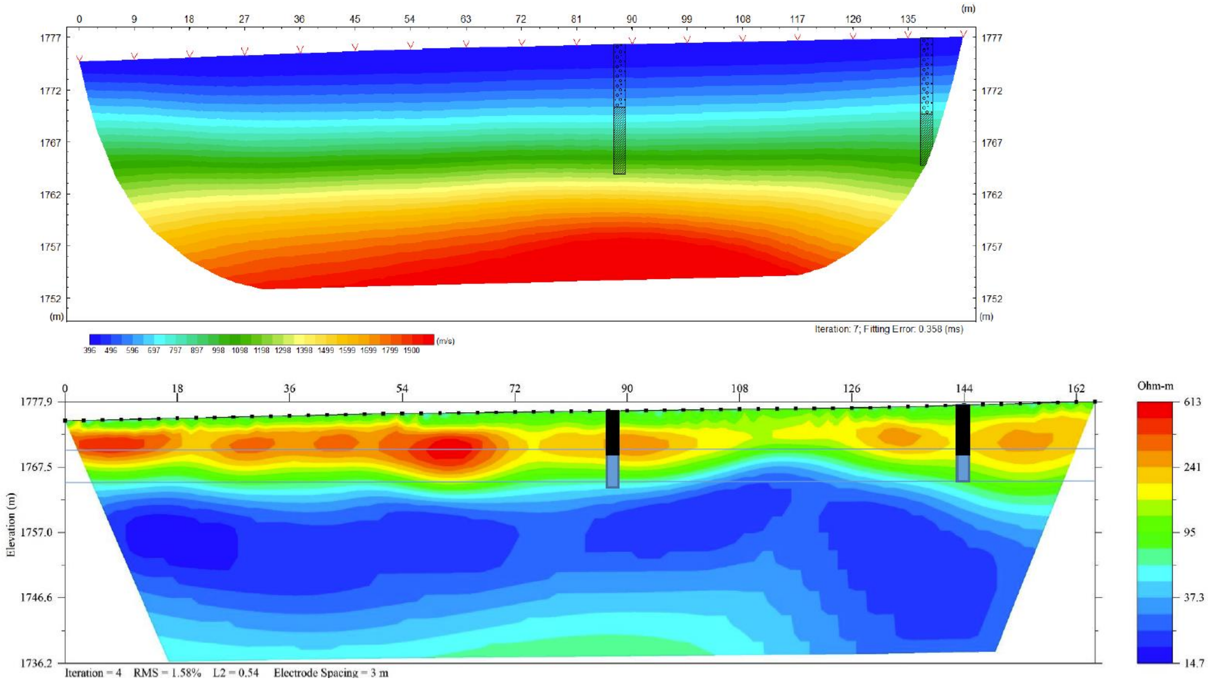

Figure 5. Seismic refraction (top) and electrical resistivity tomography (bottom) inversion results for the north-south line running along monitoring wells 5 and 6. The origin of these surveys is in the north with increasing distance values moving south toward Campstool Road. Well locations and the water levels recorded on the day of the surveys were added to the sections along with horizontal blue lines to serve as elevation markers. The transition to lower electrical resistivity values in the bottom section (roughly ~100 ohm-m) is likely caused by increasing water saturation and indicates the general location of the water table.

The generic numerical groundwater-reservoir models tested the influence of reservoir stage within the context of hydrogeology and climate. The ratio of recharge to hydraulic conductivity was found to be the primary control for predicting the existence of a subaerial seepage face just above the reservoir water surface. We defined a threshold for the development of a subaerial seepage face as (R/K)*, which we then quantified for a wide range of hydrogeologic, topographic, and stage values. We found that the relative water level in the reservoir plays a very important role in the development and resilience of the seepage face (Figure 6). In addition to (R/K)*, we used the generic modeling to also test the hydrologic controls for the length of the seepage face with a metric that we termed the seepage length fraction and the proportion of groundwater that discharges from the subaerial seepage face relative to the total groundwater discharge to a reservoir termed the seepage flow fraction.

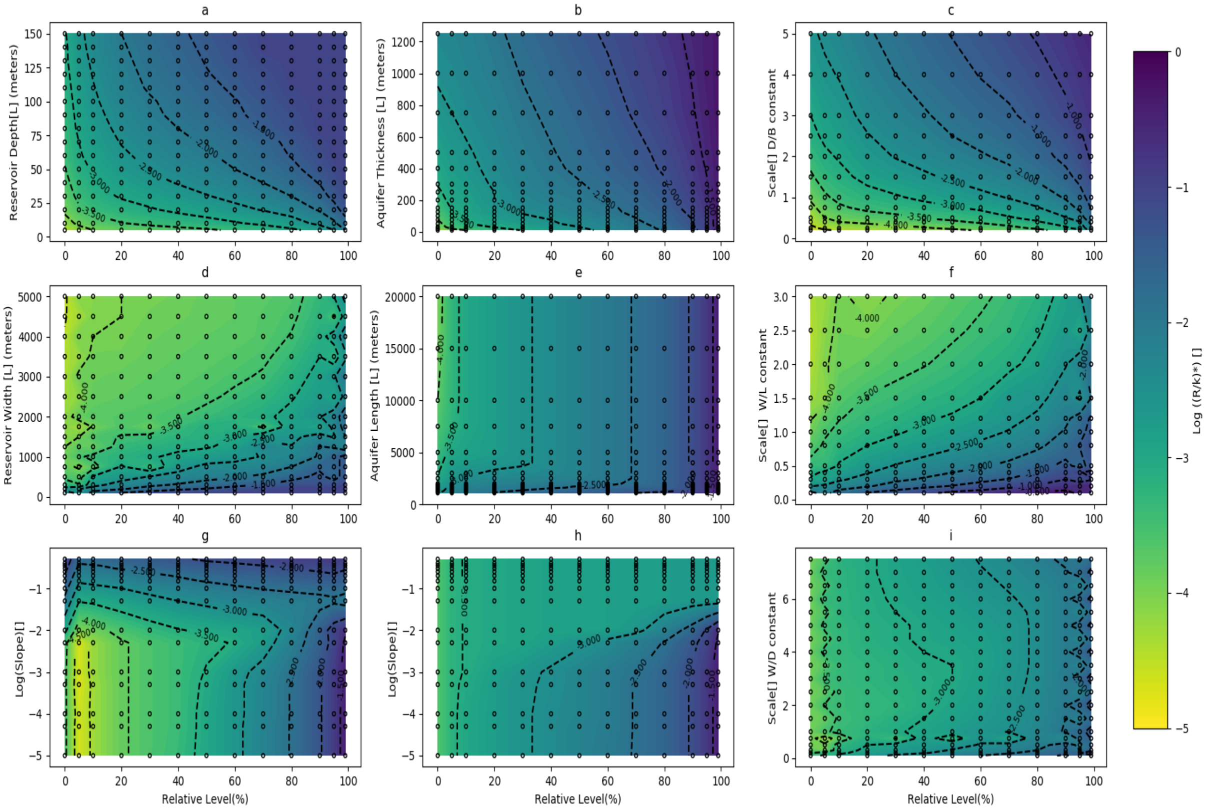

Figure 6. The onset of seepage ratio (R/K)* calculated using generic groundwater flow models for combinations of relative reservoir stage levels with topographic and geologic parameters. Each black circle represents the parameter values where the (R/K)* was simulated using up to several dozen models.

The site-specific numerical modeling study is still underway, although results from test simulations are included in this report to show some of what we will be investigating (Figure 7). These models are not yet calibrated to the field data collected as part of this project, and as such, we cannot confidently deduce any water budget or water table responsiveness from these tests. However, from these preliminary modeling results, the higher topography to the south of the reservoir appears to accommodate more water table fluctuations related to the reservoir stage changes (Figure 7b), which could indicate substantial bank storage during high reservoir stages that could maintain some flows in Crow Creek during drought. We intend to quantify this bank storage effect using the calibrated model and analyze the duration this bank storage could contribute to Crow Creek flows for various management scenarios. Alternatively, the large water table response to the reservoir stage change could also indicate that the reservoir is losing water to recharge the shallow groundwater system and may not discharge back into Crow Creek downstream. Similarly, the low variability in groundwater levels to the north of WYHRR2 could be caused by consistent groundwater discharge to the reservoir, which could provide baseflow to the reservoir and Crow Creek for all stage conditions.

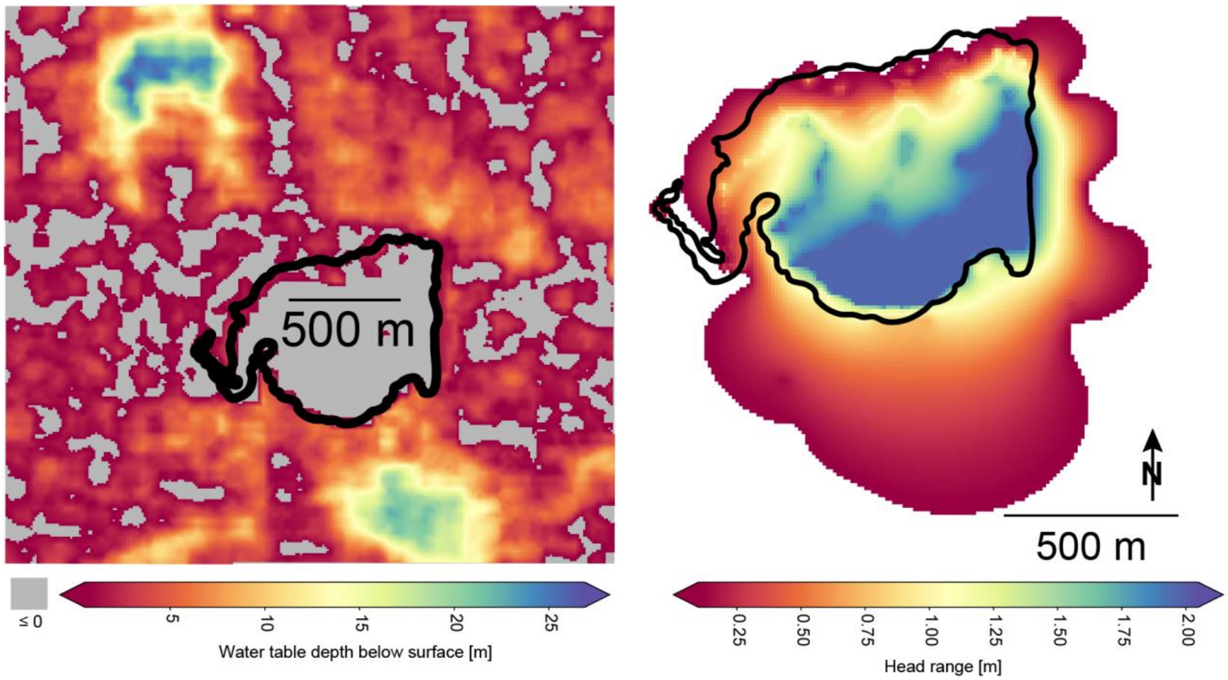

Figure 7. Preliminary WYHRR2 transient groundwater simulation results for seasonal reservoir water level changes of 2 m showing the average water table depth below the surface over a year (on the left) and the maximum range in head associated with WYHRR2 stage variations for that same year (on the right).

Significance

Our study provides both general and specific insights into how groundwater interacts with and responds to changing water levels in reservoirs. With the generic modeling study, we identify combinations of hydrologic and topographic conditions that are likely to create the supporting environment for groundwater seepage, and we show how varying the water level of a reservoir can affect these relationships. Importantly, these sites with groundwater seepage are also where fringe wetlands are most likely to be located, and the models can help to set the water level range over which these wetlands would be kept wet by active groundwater seepage. Maintaining and managing the water levels in reservoirs with seepage wetlands for the conditions identified in our generic modeling study could set the limits for resilient wetlands and be used as both a management and design tool. This generic modeling framework is a diagnostic tool that can be used to identify which systems may be most at risk in times of drought, though the method is not sufficiently complex to provide all of the information. For that reason, we also conducted the fieldwork and more detailed modeling for WYHRR2. As we continue to finalize our datasets and analyses for WYHRR2, we will create a case study for how to monitor and manage combined reservoir water levels to maximize groundwater storage. In drought, we will quantify how this additional groundwater storage is discharged back to the reservoir, leading to some amount of time where the groundwater discharge will offset the effects of the drought. Calculating the amount of time and the degree of offset are the primary focus the final steps of the WYHRR2 field and modeling study.

Publications and presentations

- Rath, P. and K.M. Befus (in prep), Reservoir water level management impacts on groundwater-surface water connections, planned submission to J. Hydrology in Fall 2021.
- Rath, P., K.M. Befus, and E. Bresciani (in prep), Formation and evolution of subaerial groundwater seepage near and to waterbodies, planned submission to Water Resources Research in Spring 2021.
- Rath, P. and K.M. Befus (2019), Impacts of reservoir stage fluctuations on groundwater dynamics, presentation at the American Geophysical Union Fall Meeting (December 2019): https://ui.adsabs.harvard.edu/abs/2019AGUFM.H41K1854R/abstract.
- Rath, P. and K.M. Befus (2018), Estimating changes in bank storage and groundwater movement due to reservoir level variations, presentation at the Wyoming Water Association (October 26th, 2018).

Student support

Several students were supported through this project:

- Prayas Rath, now a PhD candidate in Civil Engineering, was the lead graduate student supported on this project. He was funded by this project with a research assistantship for 3.5 years, including support over the summer months. His tuition was also funded by this project. Mr. Rath will be defending his dissertation proposal in Spring 2021 with the goal of defending the dissertation either in Fall 2021 or Spring 2022.
- Alexander Kurnizki, who graduated with an MS in Civil Engineering in August 2020, assisted with fieldwork over the summers on this project. He received only partial summer support and primarily helped with geophysical surveys and groundwater monitoring activities. Mr. Kurnizki will be starting as a civil engineer with the U.S. Forest Service in the Shoshone National Forest, WY in April 2021.
- Lilianne Sullivan, BS in Civil Engineering 2020, was a full-time summer undergraduate researcher funded by the project for Summer 2019. Ms. Sullivan assisted in the groundwater monitoring and geophysical data collection, managed the groundwater level time series data, and post-processed the geophysical data, including the development of Python scripts for these tasks. We were unable to reach MS. Sullivan for an update on her current employment and activities.
- Brennon Houchin, BS in Civil Engineering and BS in Architectural Engineering graduating Spring 2021, was a full-time summer undergraduate researcher funded by the project for the Summer 2018. Mr. Houchin assisted with the drilling of the monitoring wells, performed the hydraulic lab measurements on the collected cores, and he developed some Python scripts for managing the data collected during the project. Future directions could include graduate school or a full-time position with an engineering firm with the top choice being on in Wyoming.

Conferences attended

- Wyoming Water Association 2018 meeting attended by P. Rath
- American Geophysical Union 2019 Fall meeting attended by both K. Befus and P. Rath to present project findings. Only P. Rath’s travel to the conference was funded by this project.

Notable awards and achievements

- P. Rath passed his PhD qualifying exam in Spring 2019 and preliminary exam in Spring 2021.

Acknowledgements

We would like to thank Mr. Dennis Fogg for graciously allowing us to perform these field activities on his property. We would also like to thank the Wyoming State Engineer's Office for sharing water level measurements of WYHRR2, as well as for helping us to select WYHRR2 as the field site. We hope our findings are useful for your management of Wyoming's water and natural resources. We thank WYCEHG for all of the technical and fieldwork assistance with installing the monitoring wells and performing and analyzing the geophysical surveys. We also thank the Shuman lab for providing access and training on the Geotek system, and the McElroy research group for providing access to the sonar used in the bathymetry mapping.

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