Wyoming Water Research Program
Annual Technical Report
FY 2017

Introduction

The NIWR/State of Wyoming Water Research Program (WRP) coordinates participation in the NIWR program through the University of Wyoming's Office of Water Programs (OWP). The primary purposes of the WRP are to support and coordinate research relative to important water resources problems of the State and Region, support the training of scientists in relevant water resource fields, and promote the dissemination and application of the results of water-related research.

Primary participants in the WRP are the USGS, the WWDC, and the University of Wyoming. An advisory committee, consisting of representatives from State and Federal agencies, solicits and identifies research needs, recommends projects, and reviews and monitors project progress. The Director of the OWP serves as a point of coordination for all activities and serves to encourage research by the University of Wyoming addressing the needs identified by the advisory committee. State support for the WRP includes direct funding through the WWDC and active State participation in identifying research needs and project selection and oversight.

The WRP supports faculty and students in University of Wyoming academic departments. Faculty acquire their funding through competitive peer reviewed grants. Since its inception in the year 2000, the WRP has funded a wide array of water related projects across several academic departments.

Research Program Introduction

Since inception of the NIWR program in 1965, the Wyoming designated program participant has been the University of Wyoming. Until 1998, the Wyoming NIWR program was housed in the Wyoming Water Resources Center (WWRC). However, in 1998 the WWRC was closed. In late 1999, the Wyoming Water Research Program (WRP) was initiated to oversee the coordination of the Wyoming participation in the NIWR program. The primary purpose of the Wyoming Institute beginning with FY00 has been to identify and support water-related research and education. The WRP supports research and education by existing academic departments rather than performing research in-house. Faculty acquire funding through competitive peer-reviewed proposals.

In conjunction with the WRP, an Office of Water Programs (OWP) was established by State Legislative action beginning July 2002. The duties of the Office are specified by the legislation as: (1) to work directly with the Director of the Wyoming Water Development Office to identify research needs of State and Federal agencies regarding Wyoming water resources, including funding under the National Institutes of Water Resources (NIWR), (2) to serve as a point of coordination for and to encourage research activities by the University of Wyoming to address research needs, and (3) to submit a report annually prior to each legislative session to the Select Water Committee and the Wyoming Water Development Commission on the activities of the office.

The WRP, which is coordinated through the OWP, is a cooperative Federal, State, and University effort. Activities are supported by the NIWR, Wyoming Water Development Commission, and University of Wyoming. A State Advisory Committee serves to identify research priorities, recommend projects for funding, and monitor project progress. Reports for the following FY16 WRP research projects are given herein in the order listed below:

Project 2015WY88B Final Report: “High-Resolution Modeling of Precipitation, Snowpack, and Streamflow in Wyoming: Quantifying Water Supply Variations in Future Decades”, Bart Geerts, Atmospheric Science, UW, Mar 2015 – Feb 2017.

Project 2015WY89B Final Report: “Quantifying Return Flow in the Upper Wind River Basin”, Ginger Paige and Scott Miller, Ecosystem Science and Management, UW.

Project 2016WY91B Final Report: “Groundwater Modeling of the Casper Aquifer, Belvoir Ranch, Cheyenne”, Ye Zhang, Geology & Geophysics, UW.

Project 2016WY92B Final Report: “A New Multifunctional Sorbent For The Treatment Of Coproduced Waters From The Energy Industry”, Maohong Fan, School of Energy Resources and Dept. of Chemical & Petroleum Engr., UW.

Project 2017WY93B Annual Report: “Produced Water Treatment with Smart Materials for Reuse in Energy Exploration”, Dongmei (Katie) Li, Dept. of Chemical Engr., UW.

High-Resolution Modeling of Precipitation, Snowpack, and Streamflow in Wyoming: Quantifying Water Supply Variations in Future Decades

Basic Information

Title:	High-Resolution Modeling of Precipitation, Snowpack, and Streamflow in Wyoming: Quantifying Water Supply Variations in Future Decades
Project Number:	2015WY88B
Start Date:	3/1/2017
End Date:	2/28/2018
Funding Source:	104B
Congressional District:	1
Research Category:	Climate and Hydrologic Processes
Focus Categories:	Water Quantity, Climatological Processes, Hydrology
Descriptors:	None
Principal Investigators:	Bart Geerts

Publication

1. Jing, X., B. Geerts, Y. Wang, and C. Liu, 2017: Regional Climate Simulation of Orographic Precipitation in the Interior Western United States: Comparisons with Gauge and High-Resolution Gridded Datasets. J. Hydromet., 18, 2541–2558. https://doi.org/10.1175/JHM-D-17-0056.1

Final Report:
High-Resolution Modeling of Precipitation, Snowpack, and Streamflow in Wyoming: Quantifying Water Supply Variations in Future Decades

Bart Geerts, PI and Yonggang Wang, co-PI
Atmospheric Science, University of Wyoming

Abstract

This grant uses a community-supported weather forecast model to study precipitation, snowpack dynamics, and streamflow in and around Wyoming, a key headwaters region for the nation. The Weather Research and Forecasting (WRF) model has been run over a 30 year period (1980/10-2010/09) driven by actual weather (using a "reanalysis" product) at a sufficiently fine resolution (4 km) to capture orographic precipitation and runoff, which are very terrain-sensitive. Our simulations show that WRF, with a land surface model (the NOAH multiphysics scheme) accurately captures observed seasonal precipitation and snowpack build-up in Wyoming. The rather long simulation time is needed to validate statistical probabilities of extreme precipitation amounts at timescales ranging from hourly to annual, 1 April snowpack water loading, and streamflow at various times of the year for all streams in Wyoming at locations upstream of the first reservoir.

The proposal aims to answer two questions: firstly, *how well does WRF simulate the observed year-to-year variations in precipitation, snowpack dynamics, and streamflow in the headwaters region of Wyoming*? And secondly, *how is the distribution of these parameters expected to change in a changing climate*? As to the latter, a pseudo-global warming technique is used to perturb the retrospective reanalysis with the anticipated change according to the consensus global model guidance under IPCC's most likely scenario. This technique preserves low-frequency general circulation patterns and the characteristics of storms entering the domain. The model then is being rerun over 30 years with perturbed conditions representing anno ~2050, and any changes in the probability density functions of the above-mentioned parameters are examined. Thus we aim to quantify changes in water supply parameters in Wyoming not just in an average sense, but also in terms of probabilities of water excesses and shortages.

After three years of research, we are excited to report that *both questions largely have been answered*. Regarding the first question, we compared the 30-year retrospective simulation, called IWUS (Interior US), against SNOTEL and PRISM precipitation. While precipitation amounts validate very well (better than 10% over the mountains, at SNOTEL sites), the snowpack's water loading (snow water equivalent or SWE) tends to be underestimated by 20-30%. The seasonal cycle of SWE is captured well, including the rate of spring ablation. The cold season precipitation is captured so well that we can question the gauge-based gridded datasets: we have promoted the use of IWUS to question the accuracy of certain SNOTEL records and to guide the location of new SNOTEL sites by the NRCS other other agencies.

Regarding the second question, we ran the 30-year future climate (~2050) simulation, and found that while orographic precipitation will increase ~10-40% in winter (DJF), it will decrease slightly in summer. At high-elevation places, the snowpack in Colorado and Wyoming will build up at nearly the same rate, but reach a peak earlier and melt off 2-3 weeks earlier. The 1 April snowpack in CO/WY will be smaller compared to IWUS, but the reduction is not nearly as large as in the mountains of Idaho and western Montana.

In the original proposal, we called for WRF Hydro to be run offline to simulate streamflow in the WRF-simulated current and future climates. We ran into challenges calibrating WRF Hydro for the many watersheds in the Interior West, and did not complete this task. Admittedly, we underestimated the work involved. It is not possible to evaluate the land surface model's water fluxes, in particular evapotranspiration and soil infiltration, at least not to the same level of accuracy as precipitation or temperature, mainly because good-quality, reliable gridded data are not available. Therefore, and because groundwater release (in springs) depends on unresolved sub-soil water flow characteristics, the conversion of rainwater and snow melt to run-off and stream flow, requires calibration of WRF Hydro streamflow against observed streamflow (gauge data). This watershed-specific calibration (or "training") process optimally captures unknown sub-surface and surface parameters. We did work on such WRF-Hydro "training" for the upper Green River basin in WY, based on the 30-year retrospective run. Once completed, we argued that because the unknown sub-surface and surface parameters are largely permanent (not affected by climate change), the same watershed-specific training can be used to estimate changes in seasonal and extreme streamflow in an anno ~2050 climate. It turns out that because of our limited experience with WRF Hydro, and hydrology in general, and because of additional computational resources needed (WRF Hydro requires <1 km resolution over steep terrain), this task could not be accomplished, but the partial work completed will be used as basis for one or more new research proposals, in collaboration with a hydrologist.

Major research findings and education activities

1. Relevance to critical regional and State water problems

Water is essential to the economy and the natural resources of the arid western USA. The interannual variation of water availability is significant in this region, and remains essentially unpredictable. In a warming climate, the snowpack may melt off earlier in spring and water may become less readily available in the warm season for most years. But predictions of the climate over the next few decades are highly uncertain, especially regarding precipitation, snowpack dynamics, and streamflow. And an average change carries far less meaning in Wyoming than a change in probabilities of a dry or wet year.

Gaining a better understanding of such change matters. For instance, water treaties between Wyoming and its neighboring states involve rigid parameters such as growing season streamflow expectations based on 1 April snowpack conditions. Long-term changes in the relationship between the snowpack's water loading on 1 April and spring runoff are entirely speculative at this time, and better guidance would be most welcome, for instance to the State's Engineer's Office. A better understanding of long-term changes in typical and extreme patterns of snowpack accumulation & ablation and in seasonal water discharge in the North Platte, the Snake, and especially the Green River watersheds is of great interest to Wyoming's water obligations and water development opportunities, as well as to agricultural and forestry interests in the state, and to downstream stakeholders.

2. Objectives

The objectives of this project are twofold: firstly, we calibrate the WRF model, with atmospheric physics choices determined in our previous work, by selecting land surface parameter choices that optimally simulate a 30-year record of precipitation, snowpack dynamics, and streamflow in the headwaters region of Wyoming. And secondly, we use this calibrated WRF model to examine differences in the distribution of precipitation, snowpack SWE, and streamflow in a 2050s climate, compared to the climate of the last three decades. The term “distribution” implies that we do not only examine the mean, but also the spread and the probability of extremes. The focus is on the seasonal cycle and specific times of the year (e.g. 1 April, by which time water allocations to downstream states have to be negotiated), but we also look at daily and hourly precipitation distributions and their changes, because of the relevance to agricultural interests and hydraulic structures engineering.

3. Methods, procedures, and facilities

3.a Numeric model and validation datasets

The Weather Research and Forecasting (WRF-ARW) model version 3.7.1 is applied to the western interior U.S. (**Fig. 1**). The computational domain has 420 × 410 grid points with 51 stretched vertical levels topped at 50 hPa. The model domain has a 4 km grid spacing in the horizontal, which is fine enough to resolve deep convection and the details of the terrain. The model integration is conducted over a 30 year period from 1 October 1980 through 30 September 2010. The model was configured with the Thompson cloud microphysics scheme, the Rapid Radiative Transfer Model (RRTMG) shortwave and longwave radiation scheme, the Yonsei University (YSU) planetary boundary layer scheme, and the revised Monin-Obukhov surface layer scheme, as well as the Noah-MP land surface schemes. No cumulus scheme is used because the 4 km resolution can resolve convection explicitly. These schemes were chosen based on the sensitivity investigation of three years of 4 km WRF simulations over the studied domain (Fig. 1) for three parameters. i.e., the monthly mean diurnal minimum and maximum temperatures and monthly precipitation, including snow accumulation during the cold season. Validation datasets include all SNOTEL (Snow Telemetry) sites, providing precipitation rate and snowpack snow water equivalent (SWE), and the 4 km PRISM (Parameter-elevation Regressions on Independent Slopes Model) estimates of monthly mean values of precipitation and temperature.

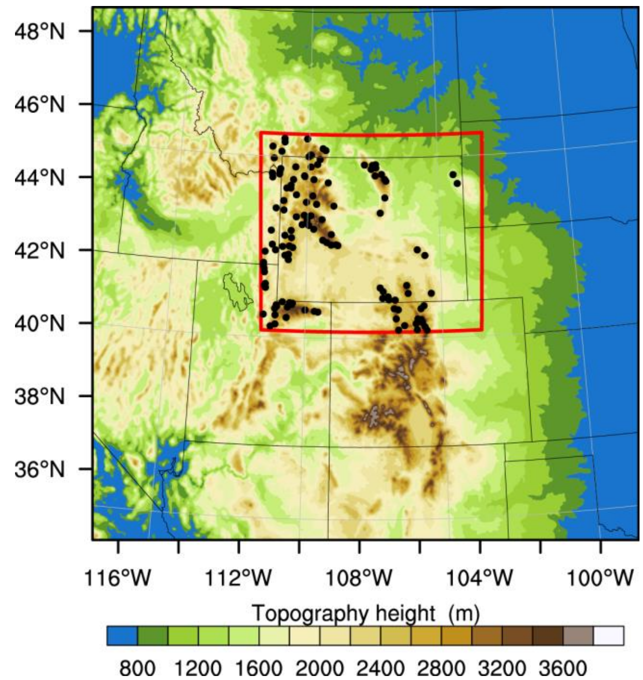


Fig. 1: Model domain of the 4-km regional climate simulation. The black dots are SNOTEL sites within Wyoming and vicinity.

3.b Current climate reanalysis data, CMIP-5 model guidance, and the PGW technique

Several “reanalysis” products (i.e., balanced 3D representations of the atmosphere and the underlying surface at a specific time in the recent past) have been developed. The Climate Forecast System Reanalysis (CFSR) is used in this work to provide initial and lateral boundary conditions. This dataset has a 0.5° x 0.5° spatial resolution and a 6-hourly temporal resolution.

The 2050s climate uses the same reanalysis data in the same domain at the same resolution, but the initial and boundary conditions are continuously perturbed using the pseudo-global-warming (PGW) technique.

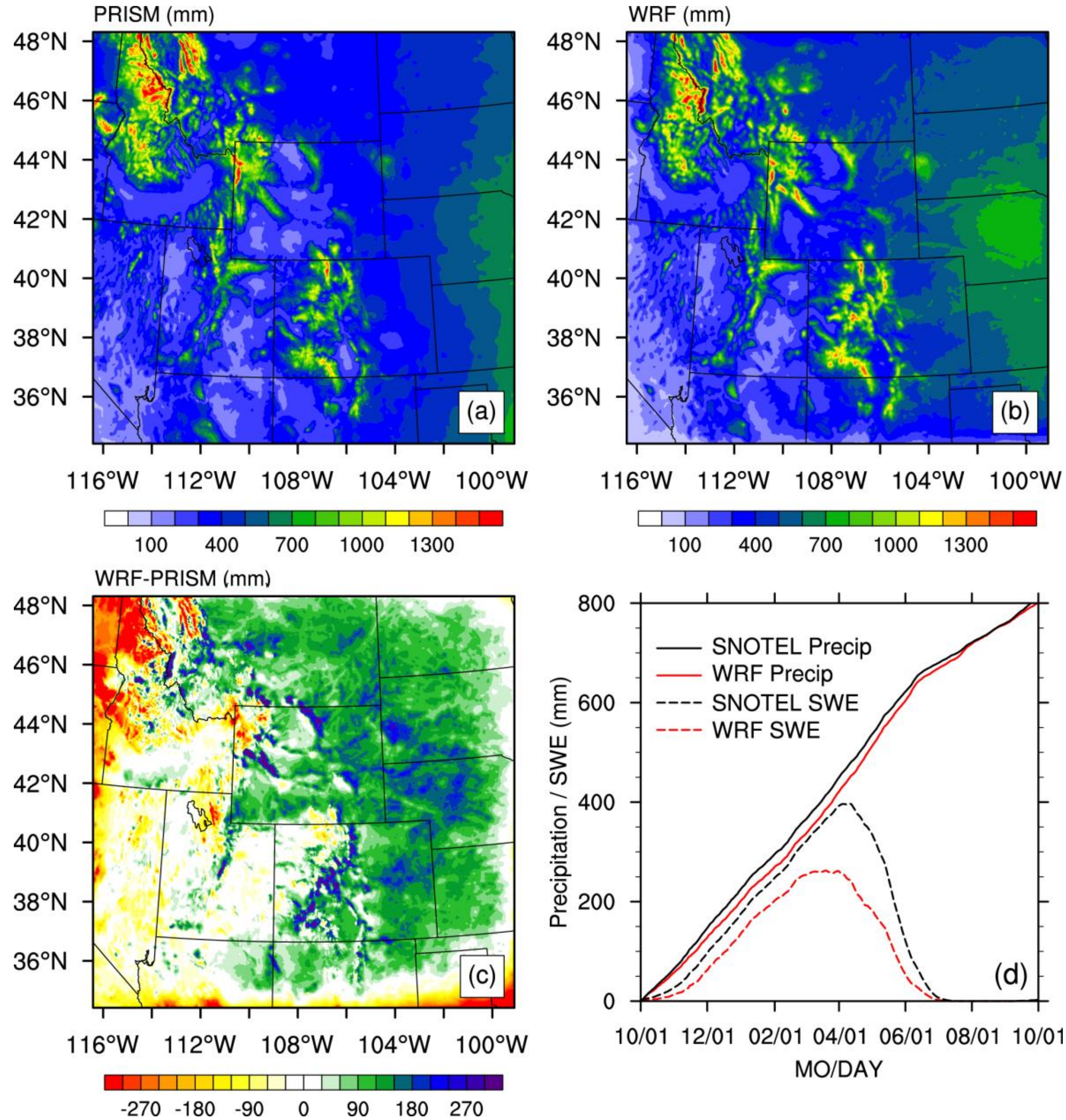


Fig. 2. Evaluation of 30 years of WRF (3.7.1) simulations. (a) PRISM annual precipitation; (b) WRF annual precipitation; (c) absolute difference between (b) and (a); (d) average seasonal precipitation accumulation and snowpack SWE at all SNOTEL sites shown in Fig. 1 as modelled (WRF) and observed (SNOTEL).

The perturbations are the monthly-mean Coupled Model Intercomparison Project 5 (CMIP-5) predicted changes in a 50-year period. The PGW technique allows unbiased climate change assessment relative to current low-frequency variability such as El Niño. The PGW technique is based on the premise that changes in intra- to inter-annual atmosphere-ocean teleconnections are inadequately understood, therefore it is best to preserve low-frequency general circulation patterns and the characteristics of storms entering the domain. We have followed NCAR's guidance as to which the ensemble of 19 CMIP-5 models has been used. All climate models have been run for several emission scenarios out to 2050 and beyond. We have used the Regional Concentration Pathway 8.5 scenario, as it is the most likely one.

3.c NCAR Wyoming Supercomputer Center (NWSC)

The proposed modeling work would not be possible without access to the facilities at the NWSC, in particular the Yellowstone system and massive data storage. Our current work has been supported by three separate NWSC allocations totaling 18.96 M core hours on Yellowstone. Large Allocation Requests under the "Wyoming allowance" can be submitted twice a year, most recently in May and November. These are no-cost high performance computing requests, reviewed by the Wyoming–NCAR Resource Advisory Panel (WRAP). This opportunity is designed specifically for federally-funded research in atmospheric, earth system and closely related sciences. The present grant from the UW Office of Water Programs (partly funded by the USGS) qualifies for a large NWSC allocation request. We received a new allocation in Aug 2016 for 6 M core hours on Yellowstone, of which 1.8M core hours remains unused at this time (1 May 2017).

4. Progress to date

4.a Retrospective simulations: the IWUS dataset

In July 2015 we completed the full 30-year simulation using an earlier version of WRF (v. 3.5.1). After some analysis we found a characteristic, seasonally dependent spatial precipitation bias pattern across the mountains, changing sign across the continental divide range. This bias remained small in the first 20 years of simulations, but became quite large in the last 10 years. WRF developer Jimy Dudhia found that it was caused by a deficient treatment of lateral boundary conditions, causing severe problems for long-term (multi-decadal) simulations particularly when a very high resolution is used. This bug was fixed in the new version 3.7.1. We completed the entire 30-year simulation with WRF v. 3.7.1 in June 2016. Results for this simulation are shown in **Fig. 2**.

Wang et al. (2017a) describe this new 30-year retrospective simulation, which we refer to as IWUS, or *Interior Western United States* simulation, to contrast it against NCAR's CONUS (CONtinental US) simulation (Liu et al. 2016, in *Climate Dynamics*). Wang et al. (2017a) describes describe WRF's architecture, calibration technique, and performance in comparison with SNOTEL (precipitation) and PRISM (precipitation and surface temperature) datasets, and also a comparison with CONUS. Results show that WRF v3.7.1 accurately captures observed seasonal precipitation, snowpack build-up, and snowpack ablation in the headwaters region around Wyoming (Fig. 2). The differences in annual precipitation between WRF and PRISM are quite small compared to the total (Fig. 2c against Fig. 2a or b). WRF seems to overpredict precipitation in the high ranges of the Wind River and Bighorn mountains. This may reflect an underestimate in the PRISM dataset (there are no SNOTEL sites above the tree line). WRF may slightly underestimate precipitation over lower ranges, such as the Wyoming range, Yellowstone NP, and the Sierra Madre. Precipitation is overestimated in the High Plains, mostly because thunderstorm activity is overestimated in summer. Please ignore the WRF underestimation along the upstream domain boundaries. In short, it is captured quite well in the Colorado-Wyoming headwater region (Fig. 2c). Overall, WRF underestimates precipitation by 7% at the SNOTEL sites shown in Fig. 1 (Fig. 2d).

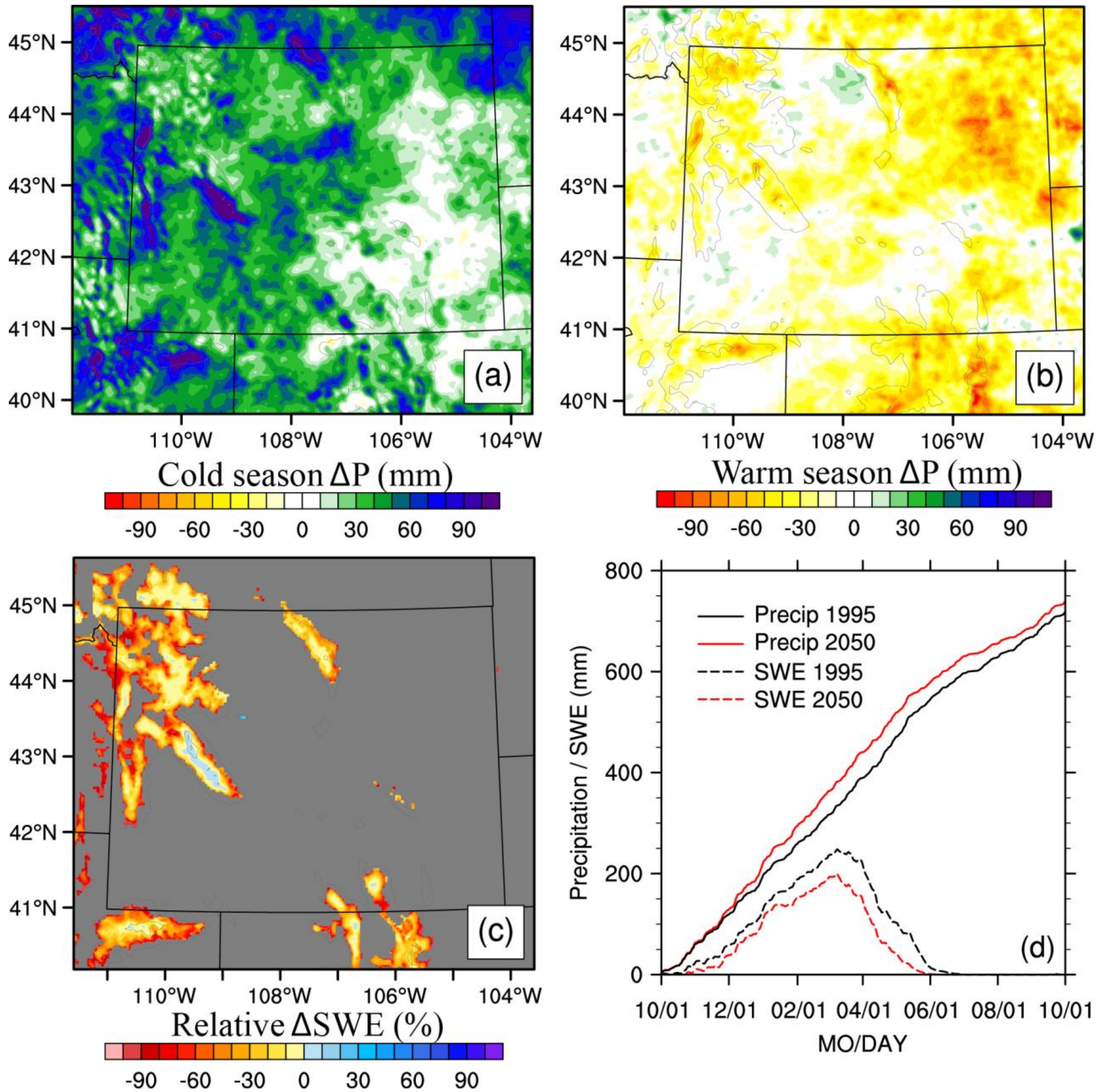


Fig. 3. Comparison of 30 years of retrospective and PGW simulations over Wyoming and vicinity. (a) The 30-yr average difference of precipitation during the cold season (future minus current); (b) same as (a), but for warm season; (c) the 30-yr average difference of SWE on 1 April (future minus current); (d) average seasonal precipitation accumulation and snowpack SWE at all SNOTEL sites shown in Fig. 1 from retrospective (black curves) and PGW (red curves) simulations. The thin grey contours in (a)-(c) show the terrain.

Snowpack dynamics at SNOTEL sites in this region are captured well (Fig. 2d), although the SWE are underestimated somewhat, by 20-30%. The seasonal distribution of SWE is captured well in particular the rate of spring ablation.

The retrospective and future simulations are archived by the USGS North Central Climate Science Center, through a framework agreement with the director (Dr. Morisette). Thus, the data are publically available at this time.

Jing et al. (2017 paper, presented orally at an AMS meeting in 2016) compares precipitation simulated by WRF with that from the datasets of SNOTEL, PRISM, and National Centers for Environmental Prediction (NCEP) National Hourly Multisensor Precipitation Analysis Stage IV dataset, using the 10-year subset of the 30-year retrospective simulation described in Wang et al. (2017). The results show WRF compares well against SNOTEL, especially for wintertime precipitation, as well as against NCEP IV and PRISM in the plains and valleys in the vicinity of NEXRAD radars. However, NCEP IV significantly underestimates orographic precipitation. PRISM is good in areas near SNOTEL sites but questionable in areas without gauges, esp. in areas above the treeline. Statistical analysis of wintertime precipitation suggests the bias and correlation between PRISM and WRF depend on gauge density and elevation.

4.b PGW simulations

We conducted the 30-year future climate simulations centered on 2050 using the PGW technique over the same domain in Fig. 1. The results indicate 10-30% more precipitation over Wyoming and vicinity in winter (DJF) (Fig. 3a), but summer precipitation decreases slightly (Fig. 3b). Less SWE is predicted on 1 Apr in future climate (Fig. 3c), and a significantly earlier date of peak SWE and earlier snowmelt at most places (Fig. 3d), except at high-elevation places (> ~3,300 m MSL), on account heavier spring snowfall there. The fraction of precipitation falling as snow decreases in future climate, especially at elevations between 6000-8000 ft MSL (not shown). We completed the WRF v3.7.1 future climate simulation in late June 2016. Since then we have been using the results to examine the effect of climate variability and projected global warming on the statistical distributions of precipitation amounts and SWE in the interior western US (Wang et al. 2017b).

4.c Publications

Jing, X., B. Geerts, Y. Wang, and C. Liu, 2017: Regional climate simulation of orographic precipitation in the Interior Western United States: comparisons with gauge and high-resolution gridded datasets. *J. Hydromet*., 18, 2541–2558. https://doi.org/10.1175/JHM-D-17-0056.1

Wang, Y., B. Geerts, and C. Liu, 2018: A 30-year convection-permitting regional climate simulation over the Interior Western United States. Part I: validation. *Int. J. Climat*., in press.

Wang, Y., B. Geerts, and C. Liu, 2018: A 30-year convection-permitting regional climate simulation over the Interior Western United States. Part II: changes in precipitation and snowpack by 2050. *Int. J. Climat.*, in preparation.

4.d Presentations

In the last 10 months, since the completion of the IWUS retrospective and future climate simulations, we have given numerous presentations to local, regional, and national stakeholder meetings.

Wang, Y., B. Geerts and C. Liu, 2015: Regional climate simulations of cold-season precipitation and snowpack over the US northern Rockies: validation and examination of factors controlling the precipitation distribution. Presented at the 2015 annual meeting of the American Meteorological Society (AMS), Phoenix AZ.

Wang, Y., B. Geerts, and C. Liu, 2016: Precipitation and snowpack dynamics over mountains in the interior Western US in a changing global climate. Presented at the AMS 17th Conference on Mountain Meteorology, Burlington VT, 27 June – 1 July 2016.

Jing, X, B. Geerts, Y. Wang and C. Liu, 2016: Regional Climate Simulation of Precipitation in the Interior Western US: Comparisons with High-Resolution Datasets and Ambient Factors Controlling Wintertime Orographic Precipitation Distribution. Presented at the AMS 17th Conference on Mountain Meteorology, Burlington VT, 27 June – 1 July 2016

Geerts, B., 2016: Assessment of gridded precipitation estimates in the Interior Western US using a Regional Climate Simulation, and changes in precipitation and snowpack in a changing climate. Fall 2016 Wyoming Water Association meeting, Casper, 28 Oct.

Geerts, B., 2016: Assessment of changes in precipitation and snowpack in a ~2050 climate in the Cheyenne water supply watershed areas. City of Cheyenne Board of Public Utilities presentation, 29 Nov.

Geerts, B., 2017: Assessment of gridded precipitation estimates in the Greater Yellowstone Area using a Regional Climate Simulation, and changes in precipitation and snowpack in a changing climate. Yellowstone River Compact Technical Committee, Thermopolis, 6 April.

Geerts, B., 2017: Assessment of gridded precipitation estimates in Wyoming using a Regional Climate Simulation, and changes in precipitation and snowpack in a changing climate. Spring 2017 Wyoming Water Forum, Cheyenne, 11 April.

Geerts, B., and Y. Wang, and X. Jing: Assessment of Gridded Precipitation Estimates in the Interior Western United States using a Regional Climate Simulation. Presented at the 2017 Western Snow Conference, 17-19 April, Boise ID. (https://westernsnowconference.org/files/2017WSC-Agenda.pdf)

Wang, Y., 2017: Precipitation and snowpack dynamics over mountains in the interior Western US in a changing global climate. Presented as a seminar at the South-Central Climate Science Center, July 2017.

5. Student and post-doc support and achievements

This project built **Dr. Yonggang Wang**'s post-doctoral expertise in regional climate modeling and fostered his collaborative ties with NCAR. Through many visits to Boulder and close collaboration, Yonggang built on the expertise developed by Dr. Roy Rasmussen's group at NCAR in their "Colorado Headwaters project", in particular the expertise of Dr. Changhai Liu. Dr. Liu's guidance in this project has been invaluable. Undoubtedly this project was essential in Yonggang's success in landing a Research Faculty position at Texas Tech University, starting in Aug 2016. Note that Yonggang's departure did not mean an end of his commitment to this project. He has continued to work on this remotely, work for which he has been compensated in part.

Xiaoqin Jing, a PhD student, is being trained as part of this project. Her dissertation, to be defended in Aug 2017, focuses on the general validation of orographic precipitation, and the ambient factors controlling wintertime orographic precipitation distribution using the 30-year retrospective simulation. She uses the IWUS retrospective model output and gauge-based gridded precipitation datasets such as PRISM. She has accepted a tenure track faculty position in the Dept. of Atmospheric Science at Nanjing Inst. of Technology, one of the most prestigious schools in Atmospheric Science in China.

Other graduate students have used or are using the IWUS dataset. **Thomas Mazzetti** (MS student, started in Jan 2017) is using IWUS as initial and boundary conditions to drive his high-resolution simulations over the Wind River Range under seeded and natural conditions. He received support from this grant from Jan 2017 – expiration. PhD student **Adam Tripp** and MS student **Coltin Grasmick** also used IWUS, as a driver dataset for their simulations and case studies in Idaho, and received some support through this grant.

Quantifying Return Flow in the Upper Wind River Basin

Basic Information

Title:	Quantifying Return Flow in the Upper Wind River Basin
Project Number:	2015WY89B
Start Date:	3/1/2017
End Date:	2/28/2018
Funding Source:	104B
Congressional District:	1
Research Category:	Climate and Hydrologic Processes
Focus Categories:	Water Quantity, Hydrology, Irrigation
Descriptors:	None
Principal Investigators:	Ginger Paige, Scott Miller

Publications

1. Gordon, B.L., 2014. Measuring return flows. Western Confluence Magazine Vol. 1, Ruckelshaus Institute, Laramie WY.
2. Gordon, B.L., 2016. Determination of Evapotranspiration and Return Flow in a Semi Arid Agricultural System. MS thesis, University of Wyoming, Laramie, WY.
3. Gordon, B.L., 2016. Determination of Evapotranspiration and Return Flow in a Semi Arid Agricultural System. MS thesis, University of Wyoming, Laramie, WY.

Quantifying Return Flow in the Upper Wind River Basin
Update Report: June 2014 – February 2018

Principle Investigators:
Ginger B. Paige, Associate Professor, Dept of Ecosystem Science and Management, University of Wyoming, **gpaige@uwyo.edu**, (307) 766-2200.
Scott N. Miller, Professor, Dept of Ecosystem Science and Management, University of Wyoming, **snmiller@uwyo.edu** (307) 766-4274.
Additional Investigator:
Andrew D. Parsekian, Assistant Professor, Dept of Geology and Geophysics, University of Wyoming, aparseki@uwyo.edu (307) 766-3603.

Abstract:
Population growth in the intermountain west, coupled with frequent drought and the prospects of climate change, are challenging the security of water supplies and the agricultural economy in Wyoming and the region. Agriculture is the largest user of water in Wyoming and the intermountain west and accounts for approximately ninety percent of the total amount of water withdrawn from streams and aquifers. However, only a portion of applied water is consumptively used. The rest is returned to streams or aquifers. Some of the potential benefits include recharge of alluvial (shallow) aquifers that serve as underground storage reservoirs, increased likelihood of maintaining late season flow and a steadier more reliable source of water downstream resulting from the return flow pattern of an interactive stream-aquifer system. This project will apply new methods and techniques to directly quantify return flow from controlled agricultural systems in the Spence/Moriarty Wildlife Habitat Management Area in the East Fork watershed in the Upper Wind River Sub-Basin in Wyoming. This location is ideal for this study as we can work directly with the managers controlling the application and timing of the irrigation water. We will use a water balance approach at the "reach scale" to quantify the return flow in the system. To directly measure and monitor the pathways and timing, we will employ new methods in hydrogeophysics and tracers at the field scale. Geophysics tools will be used to map subsurface flow paths, monitor and quantify return flow. In addition, we will use tracers such as isotopes and geochemical markers to directly measure and monitor return flow in the system. Results from this study will be compared to an irrigation return flow study conducted in the Upper Green River Basin in the 1980s. An understanding of the quantity and timing of return water flow is critical for effective water management for downstream water users and maintaining agriculture water security in the state.

Statement of critical regional or State water problem:
Agriculture is the largest user of water in Wyoming and the intermountain west. However, increasing population in the intermountain west and changing demands on limited water resources from energy and municipal use are challenges for effectively managing our water resources. Agriculture accounts for approximately

ninety percent of the total amount of water withdrawn from streams and aquifers. However, only a portion of applied water is consumptively used. The rest is returned to streams or aquifers by overland flow, subsurface lateral flow and by percolation through the soil to an aquifer, which stores or returns it to the stream system. Some of the potential benefits of irrigation can include recharge of alluvial (shallow) aquifers that serve as underground storage reservoirs, increased likelihood of maintaining late season flow and a steadier more reliable source of water downstream resulting from the return flow pattern of an interactive stream-aquifer system. An understanding of the quantity and timing of return water flow is critical for effective water management for downstream water users and maintaining agriculture water security.

Objectives:
This study uses a water balance approach coupled with intensive field investigations and characterizations of the subsurface using geophysics tools to quantify and document return flow process in the Spence/Moriarty Wildlife Habitat Management Area (WHMA) in the Upper Wind River Basin, in Northwest Wyoming.
The specific objectives are to: 1) quantify the contribution of return flows to sustained late-season flow (baseflow); 2) assess the quality of the return-flow water; and 3) compare results of this study to the results from the return flow study of a flood irrigation system that was conducted in the New Fork in the Upper Green River Basin (Wetstein et al., 1989).

Methods:
To quantify the return flow, we are using a water balance approach at the reach scale coupled with targeted sets of field experiments designed to specifically track and quantify the water that moves through the sub-surface and returns to the stream system.

Our research efforts are focused on Bear Creek a major tributary of the East Fork in the Spence/Moriarty WHMA (Figure 1). The Bear Creek section of the Spence/Moriarty WHMA is ideal for this study as there is a well-defined irrigated section of the watershed that can be isolated to capture a reach scale water balance (Figure 2). At the upper end of the reach, water is diverted into the Fosher ditch to deliver water to the four identified fields (outlined in red.) Pressure transducers to measure water depth have been installed at key locations within Bear Creek and Fosher ditch to capture changes in flow during the irrigation season within the reach. Rating curves were developed for each site to convert depths into stream flow.

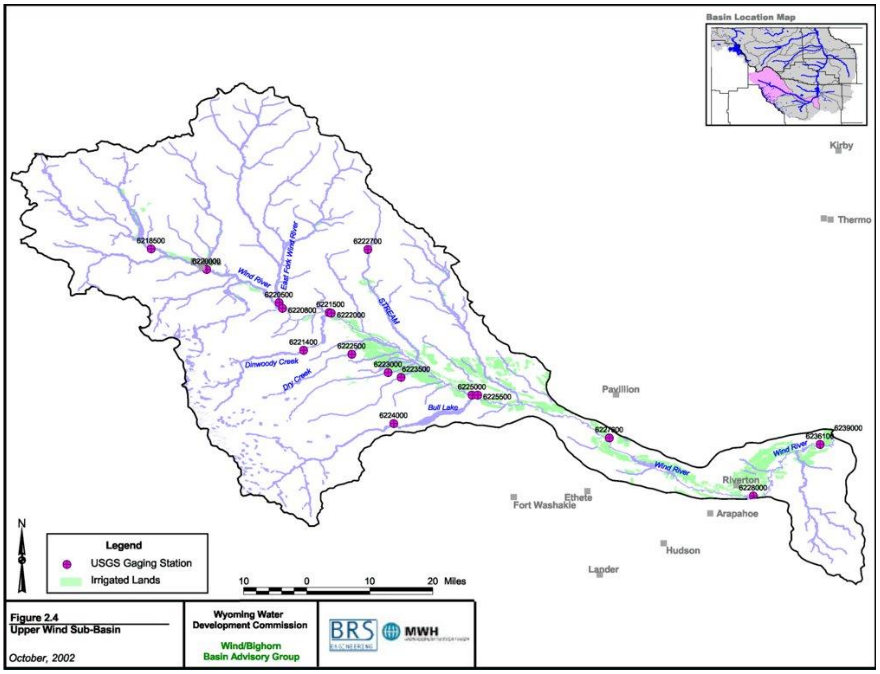


Figure 1. Location of the East Fork in the Upper Wind River Sub-Basin (courtesy: Wyoming Water Development Office *http://waterplan.state.wy.us/plan/bighorn/*)

Geophysics:
A suite of background geophysical measurements are made on each field to characterize the subsurface structure of the irrigated fields. Measurements include: Seismic, ERT, and GPR (ground penetrating radar).

Surface NMR (Nuclear Magnetic Resonance) is used to measure water content in the subsurface. Measurements are taken before and after the irrigation season in each of the irrigated fields to capture changes in soil moisture storage with depth in each irrigated field.

In 2016 we added Borehole NMR measurements. The bore hole NMR measurements are used to measure changes in soil moisture in the subsurface during the inf

Evapotranspiration:
A Large Aperture Scintillometer (which measures sensible heat flux) is coupled with a meteorological station to measure climatic conditions and evapotranspiration on one of the irrigated fields.

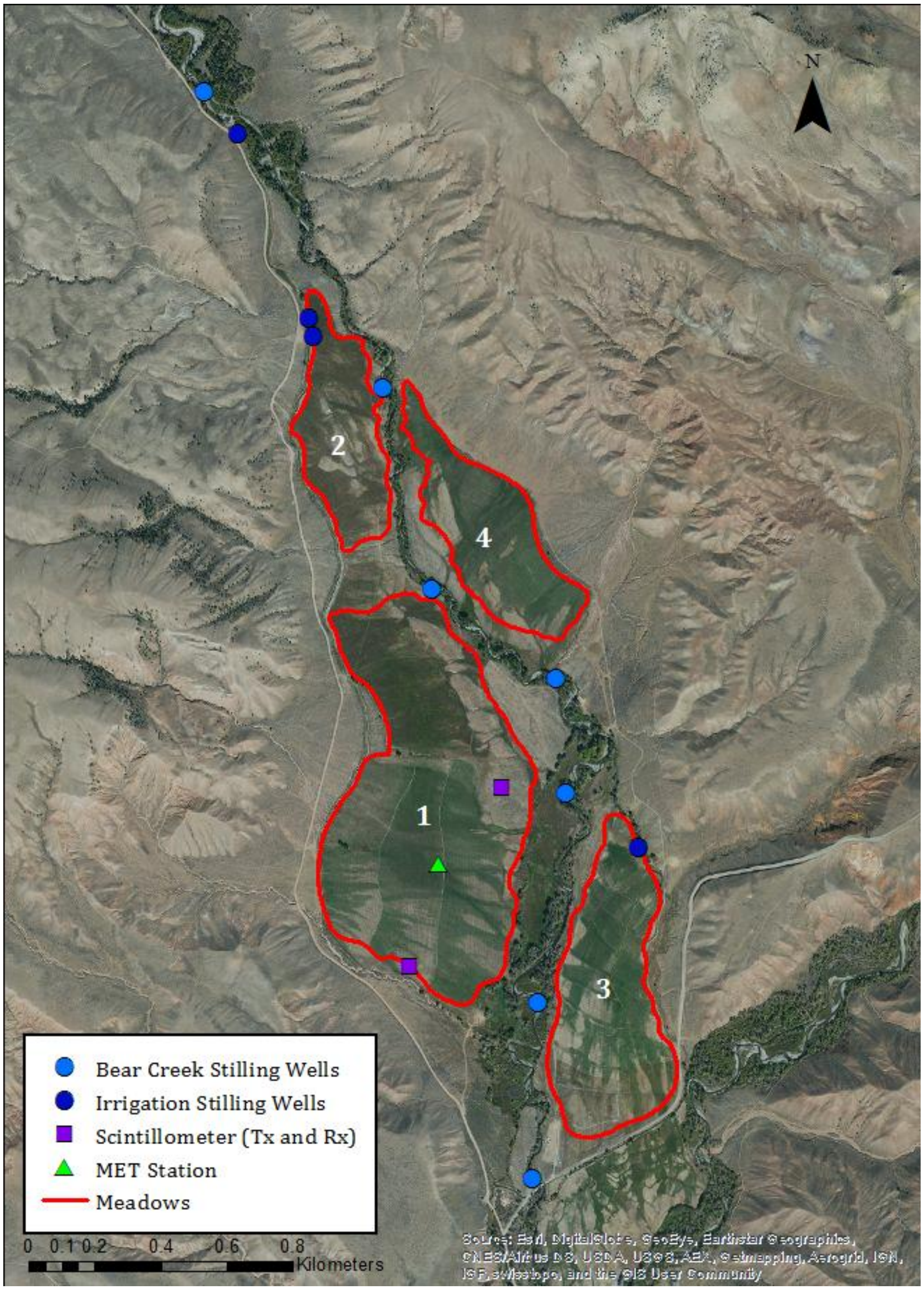


Figure 2. Location of installed instrumentation relative to irrigated meadows and stream.

Reach Scale Water Balance:

The reach scale water balance for Bear Creek is calculated using the following equation:

$$(P+Q_{IRR}) = \Delta S+Q_{RT}+(ET_B+ET_{NB})+\Sigma$$

where P is precipitation (mm), Q_{IRR} is applied irrigation water (mm), ΔS is the change in storage in the subsurface (mm), Q_{RT} is return flow (mm) = (Q_{IN}-Q_{OUT}), ET_B, beneficial evapotranspiration (mm), ET_{NB} is non-beneficial evapotranspiration - riparian vegetation (mm), and Σ is error (mm). To calculate Qrt, Q_{IN} is stream discharge at stream gage at the upper end of the reach and Q_{OUT} is stream discharge at the down stream gage.

Intensive Field Investigations:
Intensive field scale measurements using Electrical Resistivity Tomography (ERT) during irrigation are used to capture changes in soil moisture (Zhou et al. 2001). ERT measures electrical potential differences between a series of electrodes, which are generated by the electric current injected into the subsurface. The resistivity is directly related to the soil water content in the soil. We use time-lapse ERT measurements over a 60 m. transect to quantify the changes in soil water content during wetting and drying cycles over time.

Water Quality:
Water quality is monitored continuously at two locations, above and below the study reach using in-situ water quality probes. These measurements allow us to continuously monitor water quality, in particular EC and temperature, throughout the irrigation season and assess any changes in water quality with changes in flow. *We have seen no significant changes in EC over the course of the study to date.*

Progress to date:
Significant progress has been made to address the project objectives over the past two years. Much effort has been devoted to developing and refining the study design and methods to meet the site characteristics. This included focusing our research efforts on Bear Creek, a major tributary of the East Fork. The section of Bear Creek just upstream of the confluence with East Fork is ideal of isolating an irrigated reach to conduct in-depth, high-resolution investigations to quantify return flow in this system.

A large suite of hydrologic and hydrogeophysical instrumentation have been installed or deployed in the Bear Creek Study area (Table 1) over the 2014, 2015 and 2016 field seasons. Locations of the permanent instrumentation relative to Bear Creek are shown in Figure 2. Together, these measurements are used to 1) characterize the near subsurface and 2) measure the components of the water balance over the irrigation season. Though the research will continue and expand over the next year, a summary of the results to date is presented below.

Geophysics:
Background geophysical and hydrogeophysical characteristics were measured in the four irrigated meadows in 2014 and 2015. Surface NMR data were collected in June 2014 to map water content with depth. This process was repeated in 2015, but at two time steps – before and after the irrigation season - to quantify the change in water content in the subsurface over the irrigation season.

In 2016, we added a suite of boreholes for monitoring changes in subsurface flow and ground water. 3 Boreholes were installed along the ERT line (see intensive field experiments) to measure changes in subsurface water content. The borehole NMR is used to directly measure water content with depth (25 cm increments up to 10 meters) during irrigation.

In addition, 3 boreholes were installed between the irrigation fields and the riparian area to measure any changes in ground water level between the fields and the stream. These boreholes were fitted with piezometers and a pressure transducer is used to measure any changes in water table.

Table 1. Instrumentation installed in Bear Creek study area to measure components of the water balance and quantify return flow.

INSTRUMENTATION	Criteria Measured	Approx. Date
Permanent: on going		
10 Pressure Transducers (7 Bear Creek & 4 Ditches)	Water Pressure, Depth, and Temperature	Jul-'14/Jun –'15
3 Conductivity Meters (2 Bear Creek & 1 Focher Ditch)	Specific Conductance and Salinity	Jul-'14
Meteorological Station: on going		
Anemometer	Wind Speed & Direction	Jul-'14
Net Radiometer	Net Radiation (Rs, Rl, Albedo)	Jul-'14
Air Temperature Sensor	Temperature, Humidity	Jul-'14
Tipping Bucket Rain Gage	Precipitation	Jul-'14
Soil Moisture Sensors	Volumetric Water Content	Jul-'14
Heat Flux Plates	Soil temperature	Jul –'15
Large Aperture Scintillometer	Sensible Heat Flux	Sept '14
Eddie Covariance Flux Tower	Transpiration	*May '16*
PERIODIC:		
Surface Nuclear Magnetic Resonance (NMR)	Water Content in subsurface	Jun '14 Jun & Oct '15 , May & Oct '16
Borehole NMR	Water Content in subsurface during irrigation	July 2016
Electrical Resistance Tomography (ERT)	Resistance – back ground Changes in resistance during irrigation	Aug '14 & Aug '15 July & Aug '16

Seismic/Ground Penetrating Radar/Electrical Magnetic	Subsurface Structures	Jul- Aug '15

Stream flow and irrigation:
Stream flow within the reach is measured using a series of 7-stream flow gaging stations (stilling wells, Figure 2) were installed in Bear Creek and monitored over the 2014 and 2015 irrigation seasons. In addition, flow is measured in the irrigation ditches to quantify water removed from Bear Creek and applied through the irrigation system. Results from 2015 are shown in Figure 3. Rating curves developed for each of the gaging station sites had very good stage – discharge relationships (average R^2 = 0.97).

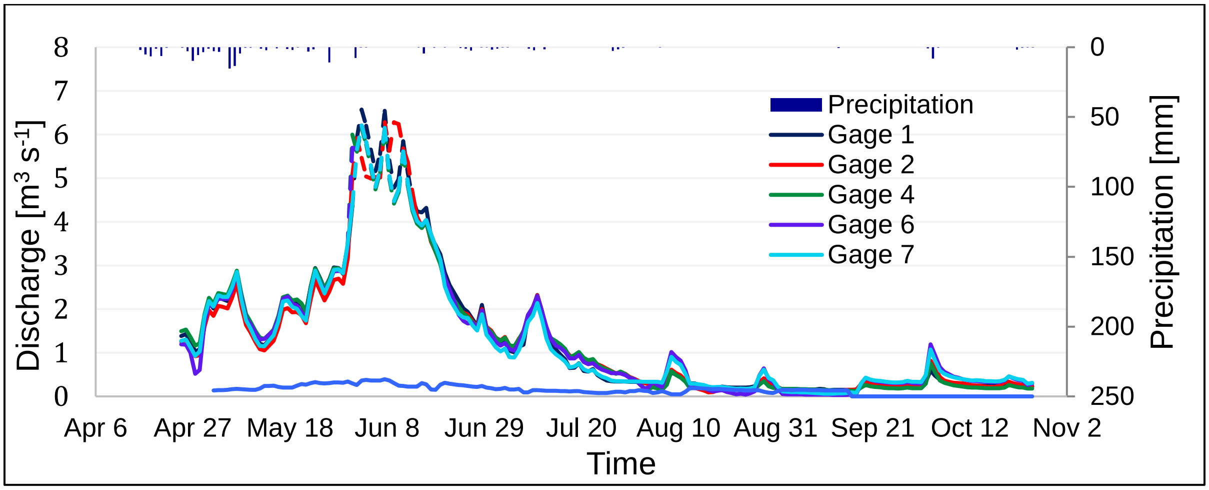


Figure 3. Seasonal hydrographs, precipitation and irrigation from all sites (2015).

Return flow for the entire reach was calculated by subtracting outflow from inflow over the irrigation season (Fig. 4). The shift in hydrographs between June 20 and August 1 shows that return flow occurs during the irrigation season.

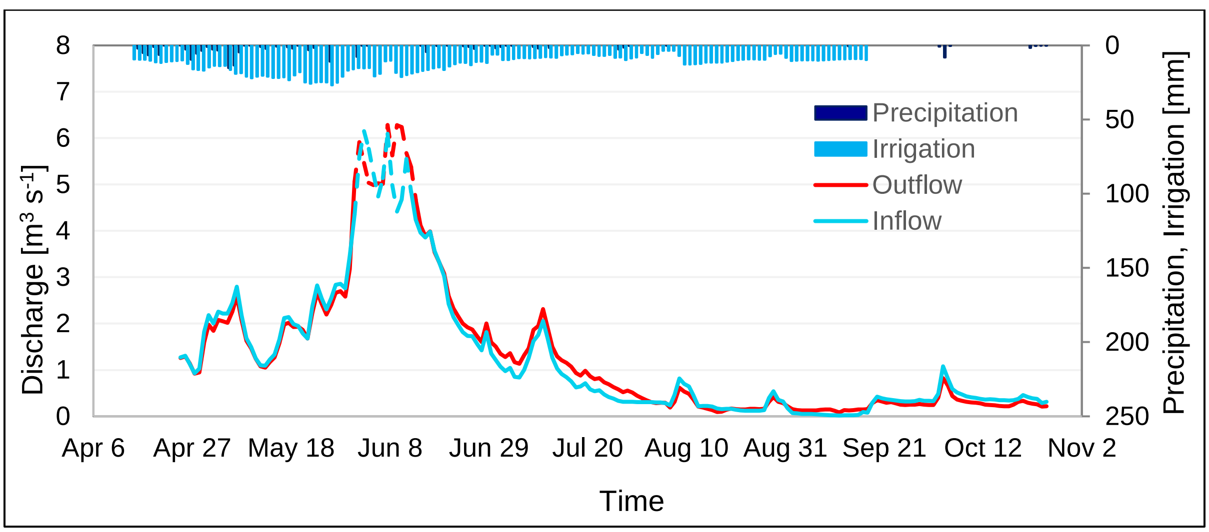


Figure 4. Inflow and outflow hydrographs used to calculate return flow (Q_{RT}).

Evapotranspiration:
Evapotranspiration for the irrigated meadow was calculated for the growing season using the scintillometer and met station measurements. The results from meadow 1 were extrapolated to the other meadows using area vegetation measurements collected before mowing of the fields. Strong correlations between Penman-Monteith and the scintillometer provided foundation for using Penman- Monteith to estimate ET from the riparian areas (Fig. 5).

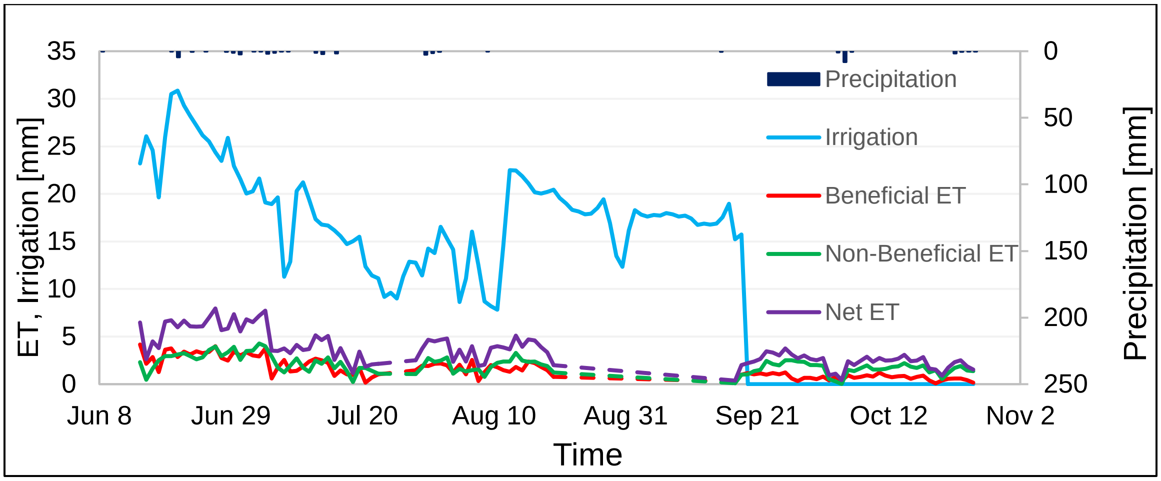


Figure 5. Evapotranspiration for the 2015 irrigation season. Non-beneficial ET is the evapotranspiration for the riparian areas calculated from using Penman-Montheith. Beneficial ET was calculated from the scintillometer.

These ET measurements using the scintillometer were continued over the 2016 field season and the results are currently being summarized and compared to the results from the Edie Covariance tower measurements.

Closing the Water Balance:
Each of the components of the water balance was measured or calculated independently for the 2015 irrigation season. This allowed us to close the reach water balance equation:

$$(P+Q_{IRR}) = \Delta S+Q_{RT}+(ET_B+ET_{NB})+\Sigma$$

$$36 \text{ mm} + 867 \text{ mm} = 110 \text{ mm} + 345 \text{ mm} + (184 \text{ mm} + 209 \text{ mm}) + 54 \text{ mm}$$

This resulted in a calculated return flow for the reach of 38.2%. This value is less than the four-year average return flow of 70% for the New Fork Irrigation district in the Upper Green River Basin (Wetstein et al., 1989). We also found that the return flow was quick and not a slow, delayed response as observed in the New Fork. This result was not unexpected due to the significant differences in the characteristics of these two basins.

Additional years of data are necessary to determine the average return flow response for this system. Similar responses were observed in the 2016 irrigation season and we are currently preparing for the 2017 irrigation season. By the end of 2017, we expect to have an understanding of the basic mechanisms and timing of the water balance over this reach.

Intensive Field Experiments:

Time lapse ERT has been used to map changes in resistivity in meadow 1 (Fig. 2) during irrigation. The changes in resistivity can be directly related to increases in soil water content (Fig. 6). These studies will be repeated and expanded over the next field season to quantify subsurface flow and map potential flow paths. These measurements, coupled with the reach water balance metrics, are being used to identify the mechanisms controlling the quantity and timing of return flow in this system.

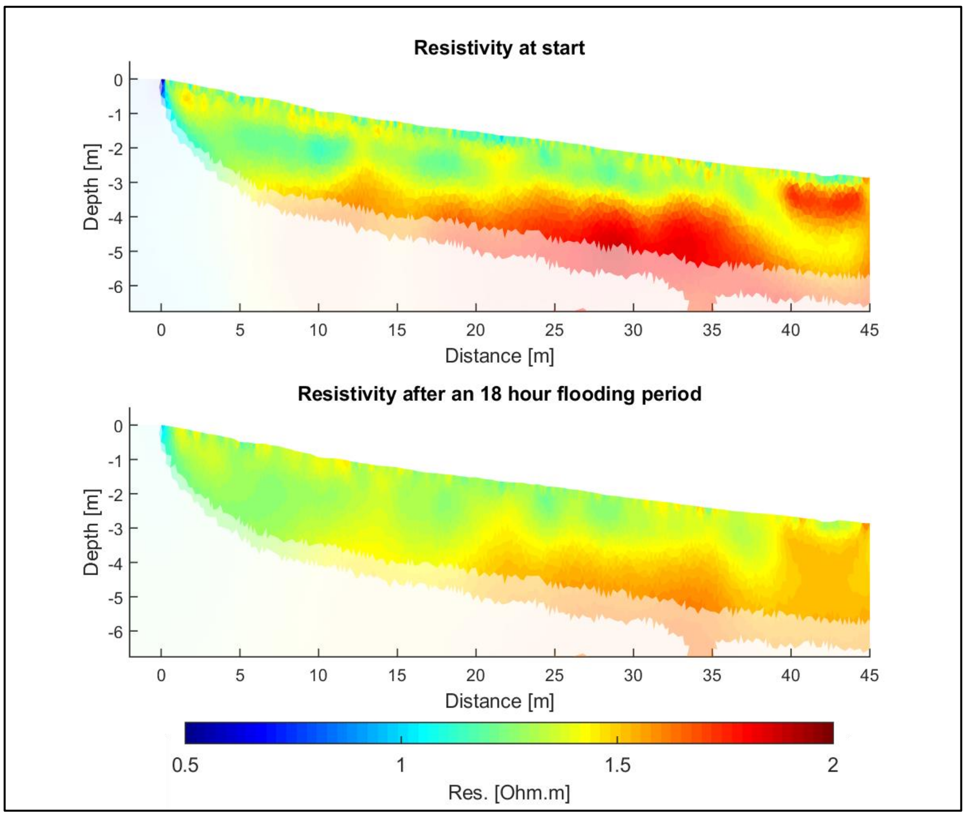
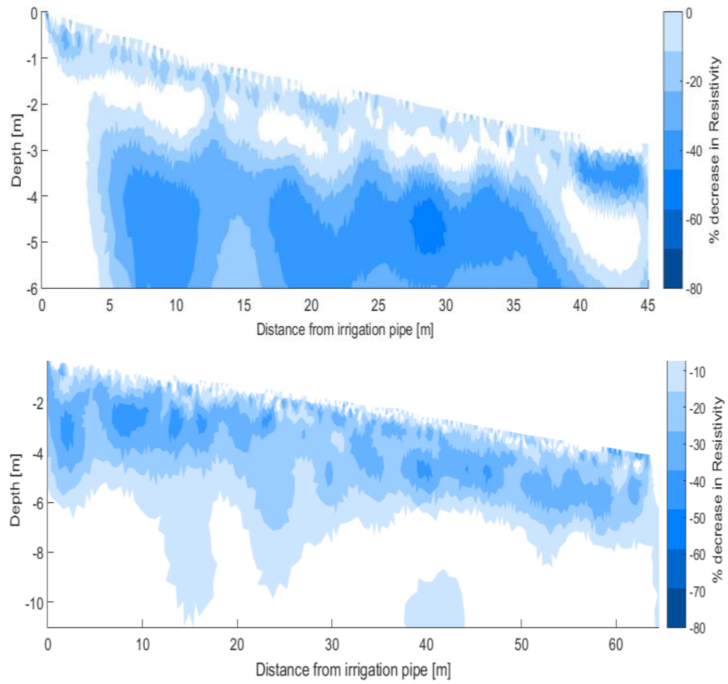


Figure 6. Time Lapse ERT during wetting and drying (before, during and after irrigation applications).

In 2016, the intensive field experiments were continued and expanded upon. We completed two wetting and drying studies and were able to map water flow dynamics in the subsurface during wetting and drying phases using time-lapse ERT and borehole NMR measurements (Figures 7 & 8.)



July 2015:
- Difference in resistivity after 18 hours of irrigation
- White areas didn't change more than 5 % from starting resistivity

June 2016:
- Difference in resistivity after 24 hours of irrigation

Figure 7. Comparison of time-lapse resistivity during irrigation experiments in 2015 and 2016. The changes in resistivity are being converted to changes in water content.

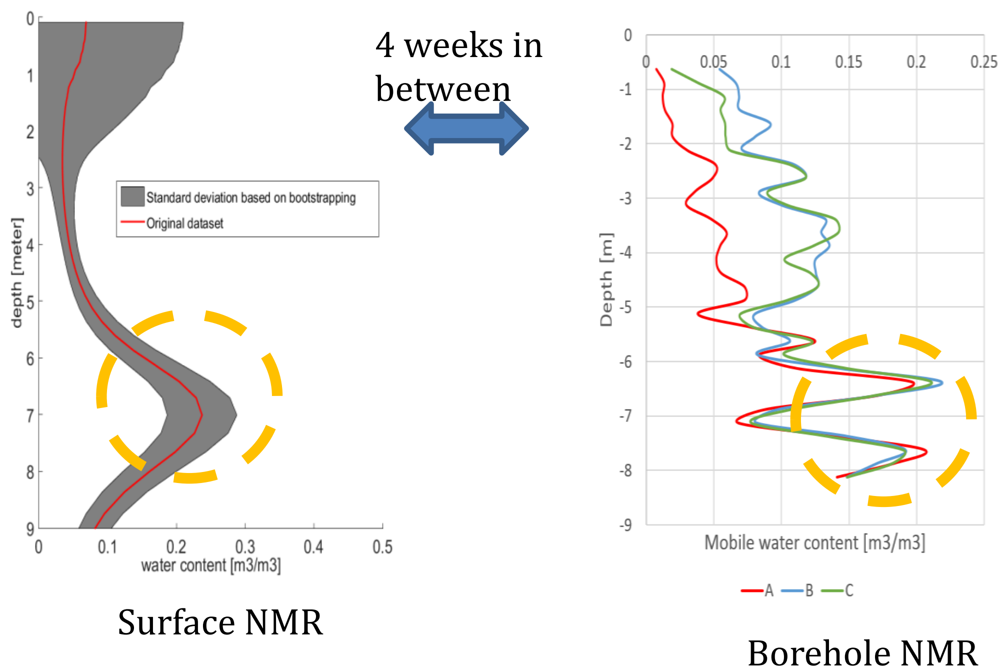


Figure 8. Comparison of results from surface NMR and time- borehole NMR showing water content increasing at the same depth in the subsurface.

In the 2017 field season we continued to measure the components of the water balance, including, ET measurements. In addition, we expanded our intensive field experiments to multiple field sites and have focused our efforts on modeling the subsurface processes. In particular we looked at the timing and advancement of the wetting front and the identification of hydrologic flow parameters.

We developed and tested a new method to determine wetting front timing and advancement using thresholds determined by set of synthetic models, based on field data. This has allowed us to identify flow regimes and timing under irrigation (see Fig. 9). We have Identified 2 flow regimes: piston-like (left part of profile) and (diagonal) preferential flow (right part of profile).

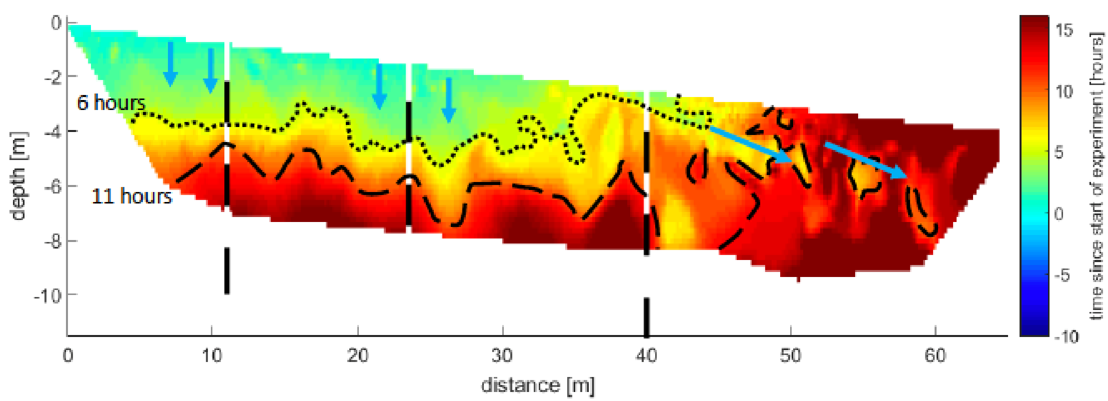


Fig. 9. Time of wetting front arrival since start of irrigation.

A correction factor was developed to account for the moment that ponding starts at the surface for each location (fig. 10): *tcorr = twetting_front—tponding_on_top.*

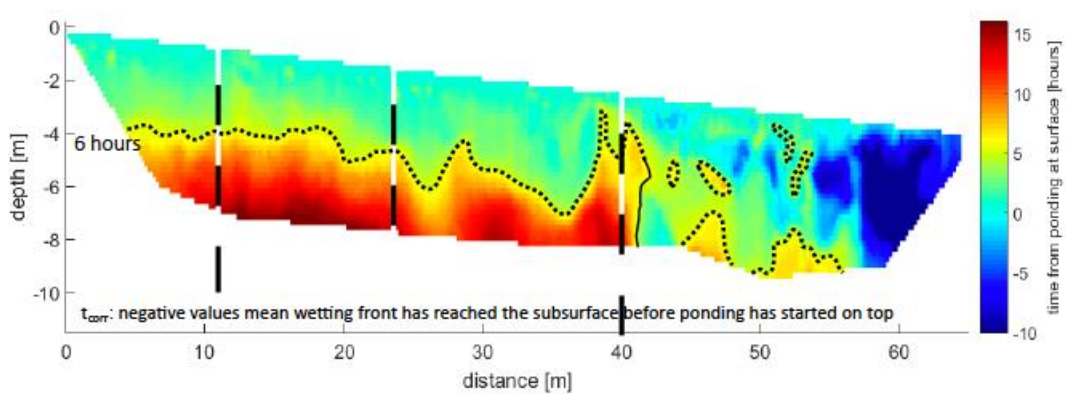


Fig. 10. Corrected time, illustrating the wetting of the subsurface after surface run-off has reached that position.

We have also focused our efforts on identifying model flow parameters including Ksat (saturated hydraulic conductivity). Using a synthetic model, we developed and tested a coupled hydro-geophysical inversion method to quantify uncertainty of vadose zone flow parameters.

Coupled hydro-geophysical inversion

Markov Chain Monte Carlo (MCMC) method

$$p(m|d_{obs}) = \frac{p(d_{obs}|m)p(m)}{p(d_{obs})} \quad ;$$

d_{obs}: measured/simulated quadrupoles

m: vadose flow model parameters

- In case of independent, identically distributed Gaussian uncertainties [2]:

$$p(d_{obs}|m) = k\,\exp(-\frac{S(m)}{s^2}) \quad \text{with} \quad S(m) = \frac{1}{2}\sum_{i=1}^{N}(g^i(m) - d^i_{obs})^2$$

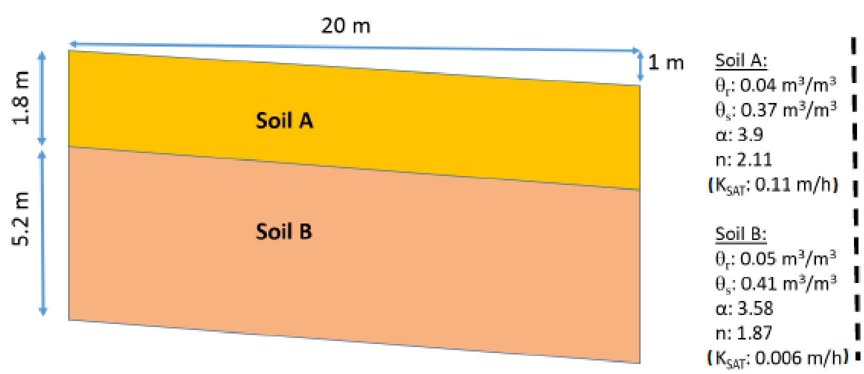
g(m): the modeled forward (geophysical) response

m: vadose zone flow parameters ; d_{obs} : measured/simulated geophysical measurements

- Each step in the MCMC chain, a new parameterset, m_{new}, is proposed based on the previous set:

$$P_{accept\_mnew} = \begin{cases} 1 & \text{If } S(m_{new}) \le S(m_{old}) \\ \dfrac{L(m_{new})}{L(m_{old})} & \text{If } S(m_{new}) > S(m_{old}) \end{cases}$$

Synthetic example



Scenarios:

- Flooding experiment: 24 h of constant 1 cm water pond-ing on top
- *Ksat* for both layers is con-sidered unknown
- Resistivity dataset collected every hour

Results:
The MCMC results in a probability distribution for the KSAT parameters (Fig. 11). The reduced sensitivity in the bottom layer of the profile leads to increased uncertainty of parameter estimates for Layer 2.

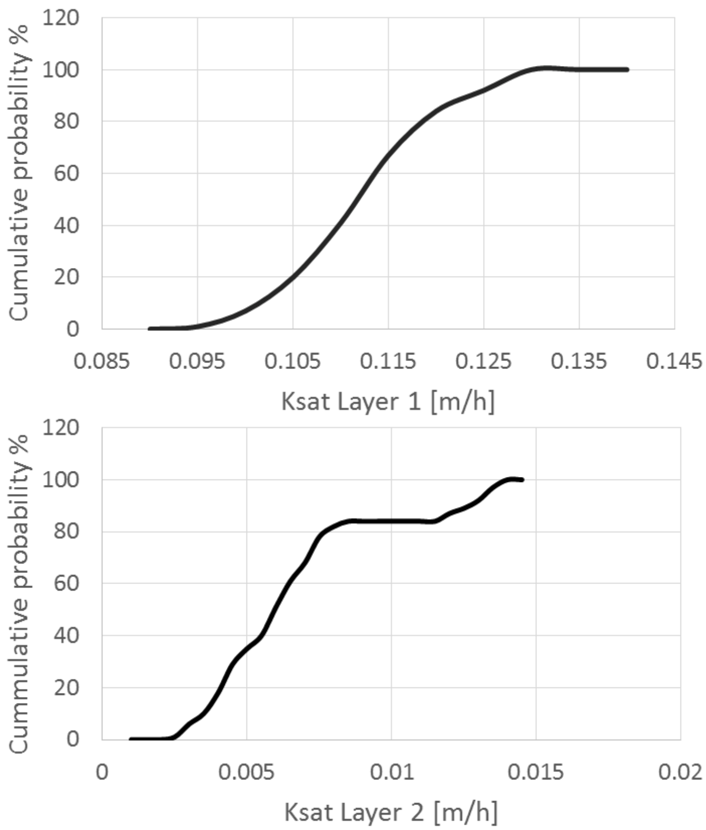


Fig. 11. Cumulative distribution for Ksat for both layers.

To date, we have been able to couple time-lapse ERT and borehole NMR inversions to identify: 1) flow paths, 2) changes in volume, timing of water content and 3) subsurface heterogeneity in multiple field sites in Bear Creek under irrigation.

In addition, we have used a Coupled hydro-geophysical inversion on a simple synthetic model to illustrate the potential to quantify uncertainty in our flow parameters. Future research will focus on increasing the complexity of the model in combination with field data. This should result in quantification of uncertainty on vadose zone flow parameters, model output and the effect of structural complexity. This step is key as we move forward to model the processes in the system.

Next Steps:

Our intensive field data collection efforts ended in October of 2017.
For the remainder of project time in 2018 we will continue our data analyses, flow modeling efforts and work on publications.

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Wetstein, J.H., V.R. Hasfurther and G.L. Kerr (1989). Return Flow Analysis of a Flood

Irrigated Alluvial Aquifer: Final Report to Wyoming Water Research Center and Wyoming Water Development Commission.

Zhou, Y. Q., Shimada, J., and Sato, A., (2001). Three Dimensional Spatial and Temporal Monitoring of Soil Water Content Using Electrical Resistivity Tomography. Water Resour. Res., Vol. 37, pp. 273–285.

Additional Project Support:

This project has leveraged additional support from two funding sources to expand the instrumentation and provide additional funding to support graduate student research.

1) Wyoming Center for Environmental Hydrology and Geophysics (WyCEHG, (NSF EPS-1208909))

2) Walton Foundation (through the Haub School of Environment and Natural Resources, University of Wyoming) provided funding for MS graduate student (Bea Gordon).

Collaborators:

Ed Kempema, Dept. of Geology and Geophysics, University of Wyoming.

Graduate Students:

Directly Funded:
Neils Claes, PhD. Program in Hydrology, University of Wyoming.
Started January 2015.

Partially Supported:
Bea Gordon, MS, Rangeland Ecology and Watershed Management/Water Resources. University of Wyoming. Defended April 2016.
Thesis Title: *Determination of Evapotranspiration and Return Flow in a Semi-Arid Agricultural System.*

Joe Cook, MS. Visiting Graduate Student from Dept., Observatoire des Sciences, Universite de Rennes, Rennes, France. Currently, PhD student in Hydrologic Sciences, Started March 2016.

Undergraduates:

Over 25 undergraduates have conducted field investigations for the project as part of the WyCEHG Geophysics Team: Collected background geophysical characteristics of the field site. (partial support for the undergraduates from WyCEHG).

Presentations:

Claes, N., G.B. Paige, A. Parsekian, S.N. Miller, E. Kempema. 2017. Quantifying Return Flow in the Upper Wind River Basin. WyCEHG 3rd Water Interest Group Meeting, Laramie, WY. October 30, 2017.

Claes, N., G.B. Paige, A. Parsekian, B. Gordon, S.N. Miller, J. Cook. 2017. Identification of surface and subsurface flow paths affecting return flow: merging hydrology and geophysics. UCOWR/NIWR Annual Meeting 2017. Fort Collins, CO. June 13-15, 2017.

Claes, N., G.B. Paige, A. Parsekian. 2017. Identification of flow paths and quantification of return flow volumes and timing at field scale. American Geophysical Union Fall Meeting, New Orleans, LA December 15-18, 2017. *poster presentation*

Claes, N., G.B. Paige, A. Parsekian, B. Gordon, S.N. Miller, J. Cook. 2017. Identifying flow barriers and subsurface flow paths affecting return flow. Symposium on the Application of Geophysics to Engineering and Environmental Problems, Denver, CO, March 19 - 23, 2017. *oral presentation*

Claes, N., G.B. Paige, and A.D Parsekian. 2016. Return Flow: a hydrogeophysical assessment of flowpaths. 2016 AGU Fall Meeting, December 14-18, 2016, San Francisco, CA. (poster)

Paige, G.B., Miller S.N., Parsekian A.D., Gordon B.L., Claes, N. 2016. Quantifying Return Flow in the Upper Wind River Basin. Big Horn Basin Planning Meeting, March 15, 2016, Worland, WY. (invited presentation)

Claes, N., G.B. Paige, A.D Parsekian, and S.N Miller. 2016. Time-lapse ERT and NMR for quantification of the local hydrologic impact of irrigation management. 29th Annual Symposium on the Application of Geophysics to Engineering and Environmental Problems (SAGEEP), March 20-24, 2016, Denver, CO. (poster)

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Claes, N., Paige, G.B, Parsekian, A.D., Miller, S.N., Gordon, B.L. 2015. Characterization of return flow pathways during flood irrigation. 2015 AGU Fall Meeting, December 14-18, 2015, San Francisco, CA. (poster)

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Claes, N., Paige, G.B, Parsekian, A. D., Miller, S. N., Gordon, B. L. 2015. Time-lapse ERT: detailed characterization of return flow from flood irrigation. RAD-seminar, 2015, 13th November, Laramie, WY.

Publications:
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Gordon, B.L. (2016). Determination of Evapotranspiration and Return Flow in a Semi Arid Agricultural System. MS thesis, University of Wyoming, Laramie, WY

Gordon, B.L., S.N. Miller, G.B. Paige, N. Claes, A. Parsekian. 201x. *A water balance based approach to quantifying return flow from irrigated fields in a semi-arid agricultural system.* Submitted to Journal of Hydrology (in revision)

Paige G.B., N. Claes, A. Parsekian, B. Gordon, S.N. Miller. 2018. Tracking agricultural water in Wyoming: Quantifying return flows to streams. Reflections. University of Wyoming, AES. Laramie, WY. (in press).

Graduate Students:
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Groundwater Modeling of the Casper Aquifer, Belvoir Ranch, Cheyenne

Basic Information

Title:	Groundwater Modeling of the Casper Aquifer, Belvoir Ranch, Cheyenne
Project Number:	2016WY91B
Start Date:	3/1/2017
End Date:	2/28/2018
Funding Source:	104B
Congressional District:	1
Research Category:	Ground-water Flow and Transport
Focus Categories:	Groundwater, Models, Water Supply
Descriptors:	None
Principal Investigators:	Ye Zhang

Publications

There are no publications.

Final Report
Groundwater Modeling of the Casper Aquifer, Belvoir Ranch, Cheyenne

Ye Zhang, Assoc. Prof., Dept. of Geology & Geophysics, Univ. of Wyoming

Abstract

During groundwater model calibration, traditional inverse methods can suffer uncertainty due to the lack of knowledge of aquifer boundary conditions (BC) and geometry which must be used in developing a forward model. In this research, a novel groundwater inverse method is combined with geostatistical analysis methods to improve the accuracy of aquifer model calibration. The new method proposes a set of hybrid formulations of the hydrological state variables (hydraulic head and Darcy fluxes), which describe piecewise approximate solutions to the groundwater flow equation. The inverse method incorporates noisy observed data (i.e., thicknesses, hydraulic heads, fluxes, or flow rates) at measurement locations as a set of conditioning constraints. Given sufficient quantity and quality of the measurements, the method yields a single well-posed system of equations that can be solved efficiently with nonlinear optimization. For a confined aquifer with two-dimensional steady state ambient flow, the calibration results include aquifer thickness, hydraulic conductivities, head and flux distribution maps, therefore the relevant BC can be extracted. When combined with geostatistical techniques such as sequential Gaussian simulation (SGS) and multi-point geostatistical (MPS), uncertainties of both estimated parameters and BC can be obtained. The solutions of the methods are stable when measurement errors are increased up to +/- 10% of the respective measurement range. When error-free observed data are used to condition the inversion, the estimated thickness is within a +/- 5% error envelope surrounding the true value; when data contain increasing errors, the estimated thickness become less accurate, as expected. The method was applied to groundwater model calibration of the Casper Aquifer at Belvoir Ranch in southeastern Wyoming, where geostatistical techniques were used to generate stochastic facies and thickness realizations conditioned to site geological, geophysical, and borehole data. These realizations were then used as input to inversion with results including hydraulic conductivity of each facies and hydraulic head distributions extending to the recharge area of the Casper Aquifer outcrops. By combining geostatistics with inversion, uncertainty in all the outcomes are also quantified. To verify field application, a cross validation was carried out with excellent outcomes. Based on the characterization of aquifer parameters and boundary conditions, a three dimensional aquifer model was built and further calibrated.

1. Problem statement

To meet future water demands, the Cheyenne Board of Public Utilities (BOPU) plans to develop the Casper Aquifer at the Belvoir Ranch as a sustainable groundwater resource. Despite several prior studies that evaluate and characterize Casper groundwater at the ranch, complex site hydrogeology (i.e., the existence of faults, foldings, fracture networks, dissolution tubes, and cavities) precludes the development of a well-informed drilling plan, i.e., where municipal water supply wells should be placed and the appropriate seasonal pumping rate, duration, and well rotations. To ensure sustainable well yield, water supply wells need to tap into aquifer regions with high hydraulic conductivities that can also capture the natural recharge into the subsurface Casper Formation. However, significant uncertainty exists in our current understanding of groundwater flow in the Casper Aquifer at the Belvoir Ranch, due to several reasons: (1) aquifer hydraulic conductivity (K) distribution is highly uncertainty, which is related to the complex site hydrostratigraphy; (2) location and rate of aquifer recharge remain uncertain; (3) aquifer boundary conditions (BC) are uncertain, e.g., at the Belvoir Ranch, the aquifer is intersected by several faults that range from impervious to flow to conductive.

2. Objectives

To develop a scientifically informed drilling program for the Casper Aquifer at the Belvoir Ranch, a study that can provide a quantitative guideline for the location and pumping condition of future water supply wells is needed. This study is aiming to integrate groundwater modeling with the existing geological and geophysical site data (including the current insights into fracture/dissolution tube distributions in the subsurface), as well as water level monitoring, recharge estimates, and dynamic well test results, to understand and quantify groundwater flow in the aquifer. A model domain for this study is defined in Figure 1, which includes both hydrostructural compartments where the majority of the data is located. It is bounded by the thrust fault to the east, Granite Springs and the associated anticline to the north, Casper outcrops to the west, and the Spottlewood Fault to the south. These geological structures serve as natural boundaries for the model, whereas this study will aim to determine their hydraulic properties and whether they are water divides or water conduits. Moreover, in consultation with Mark Stacy, our collaborator in this project, the model size will be modified by new evidence of aquifer structures. For example, a strike-slip fault north of the Granite Springs may influence aquifer behaviors at the ranch. Based on geological and geophysical data (i.e., structure deformation, seismic “bright spot”, and low electrical resistivity), a subset of these sites has been identified (with potentially enhanced Casper permeability[1]. In this study, these locations will be subject to different pumping simulations for which an individual well’s specific capacity (i.e., steady state pumping rate divided by the drawdown) will be calculated. A pumping program (rate, duration, well rotation) that can best capture the natural recharge into the aquifer, while achieving sustainable water yields will be determined at the end of this study.

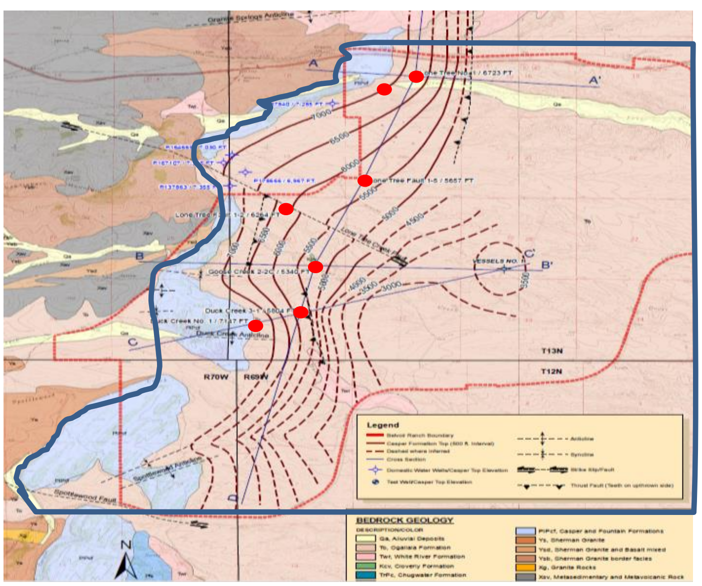


Figure 1: Study area at the Belvoir Ranch with inferred subsurface structures in the Casper Aquifer. Locations of the aquifer outcrops are shown in light blue color. Locations of four hydrostratigraphic cross sections (A-A’, B-B’,C-C’, and D-D’) are shown. The proposed modeling domain is shown by the blue outline.

3. Methodology

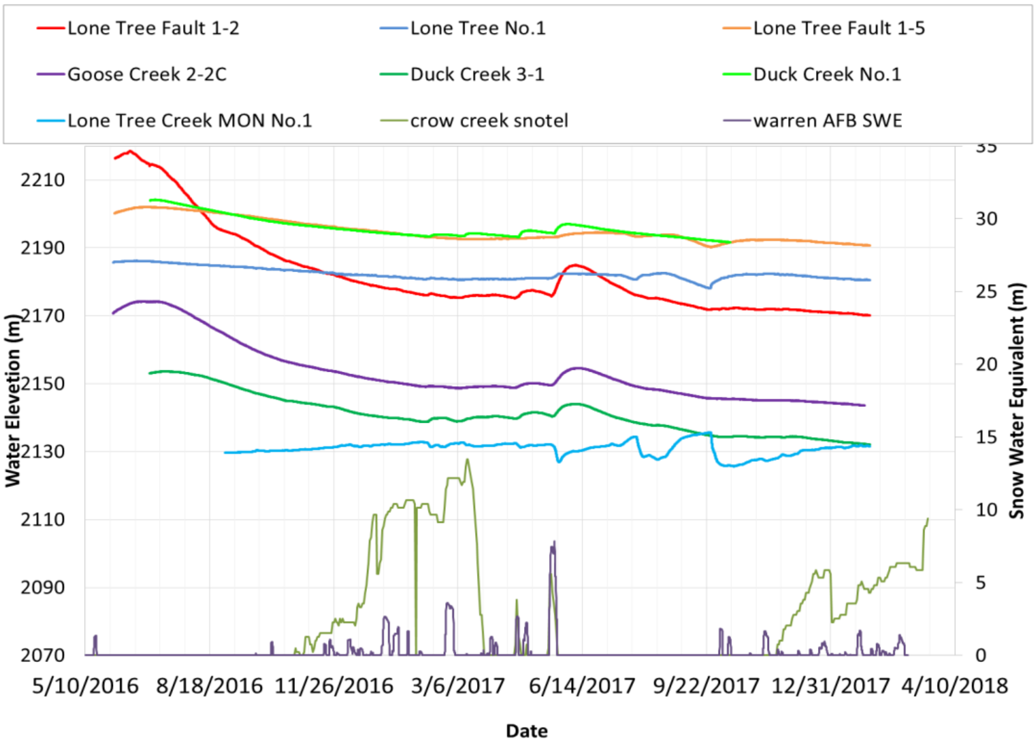
This study uses Petrel [2-3] to incorporate all site static data within the model domain to build a 3D hydrostratigraphic model, including the Casper Aquifer and its overlying formations. This model will incorporate both large-scale stratigraphic information (including the shape and extent of faults and fracture networks), as delineated by the seismic and resistivity data, and small-scale aquifer heterogeneity, as identified by the well logging data. Groundwater simulations will be performed with FEFLOW, whereas both the model parameters (Ks, storativities, and recharge rates) and the unknown model boundary conditions will be calibrated against the aquifer monitoring data using a hybrid inversion technique [4]. This hybrid technique has a potential to address complex and realistic aquifer problems by combining a novel steady-state inverse method developed by the PI's group [5-7] with a traditional, objective-function-based technique (PEST[7]) that can be used to fit transient data. The novel inverse method is physically-based, as it conserves the continuity of hydraulic head and groundwater fluxes throughout the aquifer, while its solution is conditioned to measurements that can also contain errors. Importantly, the novel method does not assume the knowledge of the aquifer BC, e.g., whether any of the bounding subsurface structures in the Casper Aquifer actually represents a no-flow or a flow-through boundary. Instead, the BC is obtained from the inverse solution. On the other hand, calibration techniques such as PEST require the precise knowledge of aquifer BC in order to accurately assess the model-data mismatch with a forward simulation model. However, aquifer subsurface BC are usually uncertain, as is discussed above for the Casper Aquifer. Even if additional wells are drilled all along the aquifer boundaries, such measurements will contain errors, which can significantly impact the accuracy of the traditional techniques.

4. Progress to date including significance

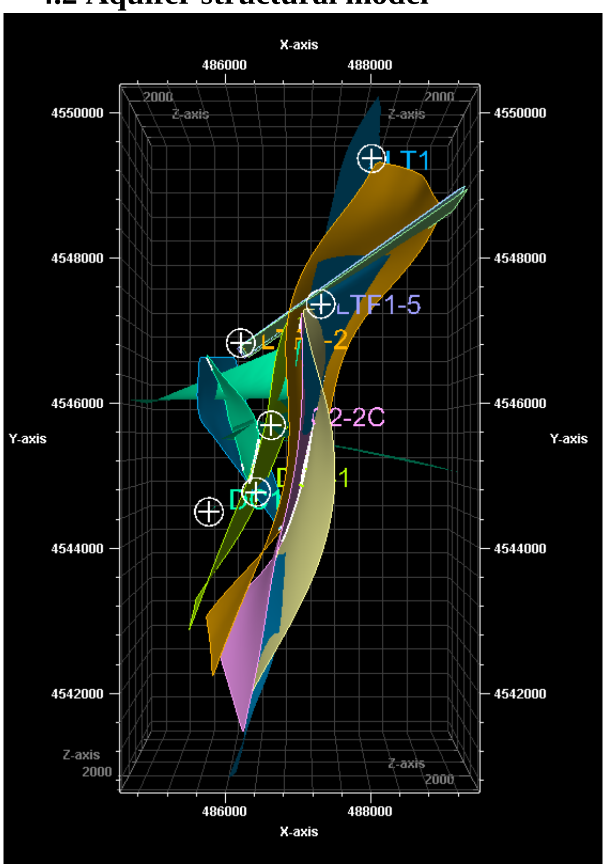
4.1 Monitoring data acquisition

From June 6th to 8th, 2016, an additional well, Lone Tree MON No. 1, was drilled and developed in Belvoir Ranch near Lone Tree Creek and is close to the existing well Lone Tree No. 1. The purpose of drilling this well is to better understand the recharge from Lone Tree Creek to Casper Aquifer. Longitute and Latitue of Lone Tree MON No. 1 are 41˚5'42.11"N and 105˚8'50.78"W, respectively. Lone Tree MON No. 1 is located between the Lone Tree Creek Sink and Lone Tree No.1. Lone Tree compartment is the most productive compartment according to pumping project. Monitoring water level data from this well will contribute to the estimation and verification of recharge rate from Lone Tree Creek to Casper Aquifer. This well has 2-in diameter, and total depth is 177 feet. The measured water level is 46.18 feet from top of casing after well completion and development. Moreover, since summer, 2016, all seven observation wells were instrumented. Water level data have been measured every thirty minutes from each of the well. These head data are then sent by the telemetry system to the server. Water level data from summer of 2016 to the most recent date has been plotted with snow depth data from nearby SNOTEL and snow stations (Figure 2). Water level data will be used for parameter and boundary condition estimation.

Figure 2: Plotted water level data with snow depth data



4.2 Aquifer structural model



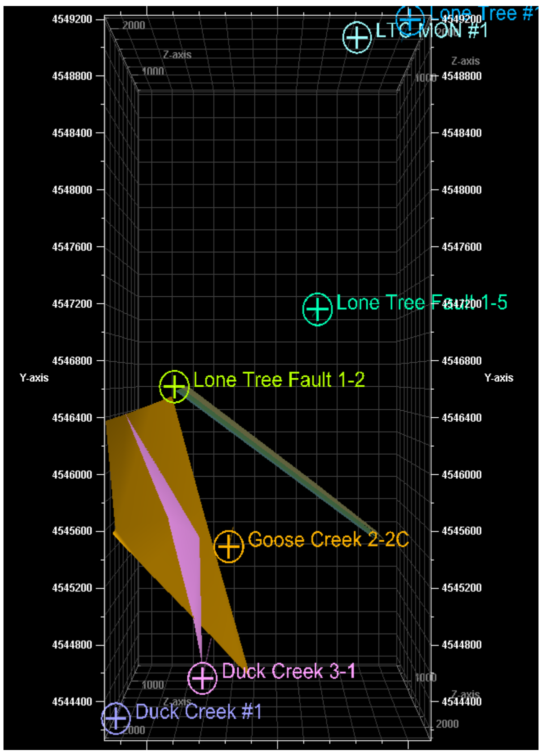
Static model has been built with Petrel by integrating the observed static aquifer structure data, including hydrostratigraphy, faults, as obtained from geological, geophysical, and logs. 2D seismic geophysical data was the soft data used to initially build the draft 3D model. Five interpreted lines from Zonge Inc. were provided [1], and then formation tops for Chugwater Formation, Goose Egg Formation, Upper Casper Formation, and Lower Casper Formation were interpreted and generated in Petrel. Locations of the faults were also interpreted from the 2D seismic data. Figure 3 is the draft fault model created with Petrel from last year's annual report.

Figure 3: Fault model created by Petrel in 2016 which is showing the interpreted faults in the site area.

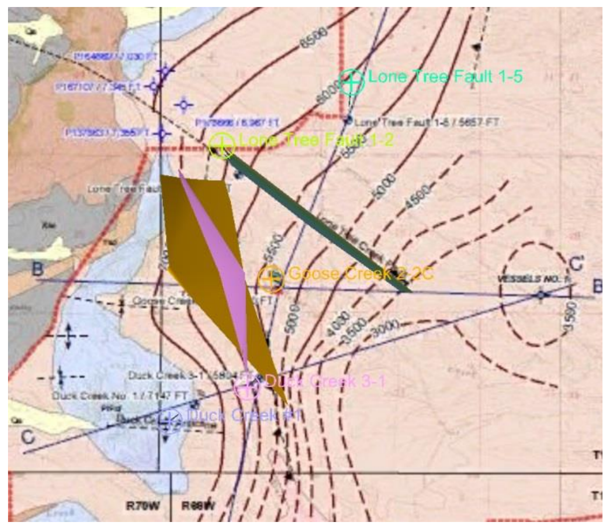
In 2017, a preliminary Petrel model was built to incorporate the three essential faults shown on the geologic map. The model built in 2016 with very complex fault system only captures two of the three essential faults shown on the geologic map.

Including all interpreted faults from seismic data is not necessarily the optimized option. Indeed, the model with three faults is a good candidate to start with since these three faults are proved both by surface geology and seismic interpretation.
The Petrel model is also rebuilt with the seismic cross sections in depth domain instead of time domain, so all of the depth units are consistent with each other. The horizons (top and bottom of each formation) of Petrel model are also reinterpreted, thus the resulted surfaces are smoother. Surfaces are cleaned based on geologic map and depositional order. The updated model is shown in Figure 4(a), and the comparison between the geologic map and the updated fault model is shown in Figure 4(b).

Figure 4: Updated Fault model created by Petrel showing three essential faults in the site area.



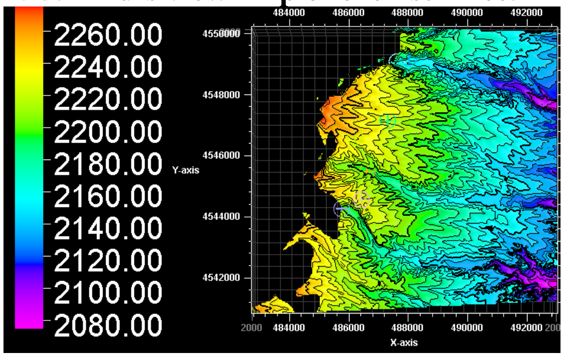
a. Updated Petrel fault model



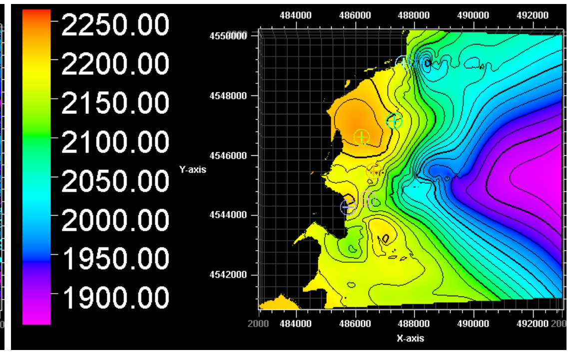
b. Comparison between the geologic map and the updated fault model

Bird's view map of each formation is shown in Figure 4. In this updated model, six horizons are made. First horizon is the surface excluding Casper Aquifer outcrop; second horizon is the bottom of either White River or Ogallala Formation, since they are the erosional formations; third horizon is top of Chugwater Formation; fourth horizon is top of Goose Egg Formation; Fifth horizon is top of Casper Aquifer, and compare to the previous model, Upper and Lower Casper formations are combined to Casper Formation for preliminary simulation; and the sixth horizon is top of Sherman Granite.

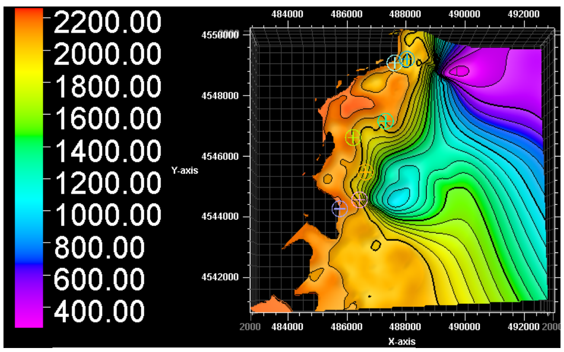
Figure 5: Bird's view map of each surface.



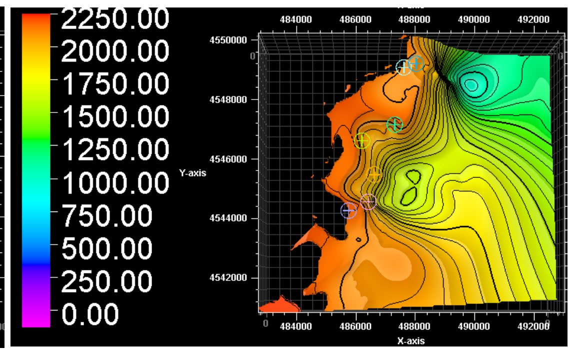
Surface excluding Casper Aquifer outcrop



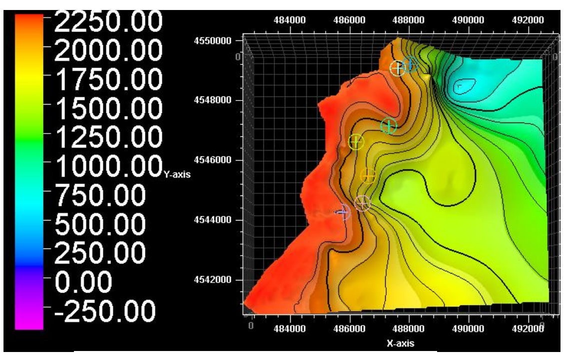
Bottom of White River and Ogallala Formation



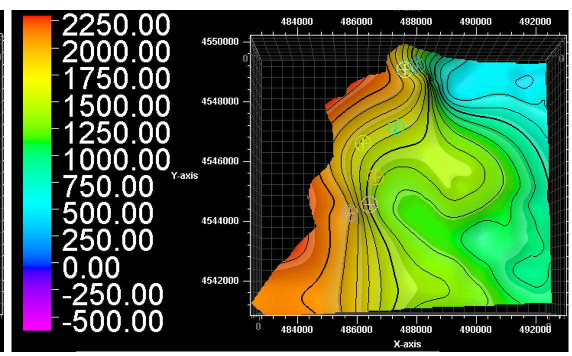
Top of Goose Egg Formation



Top of Chugwater Formation



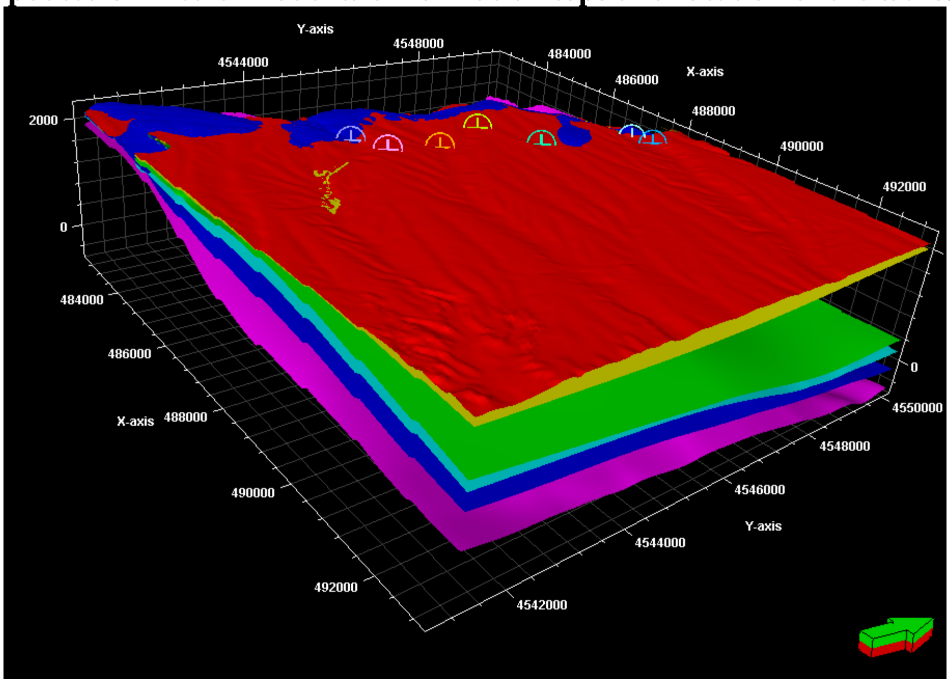
Top of Casper Aquifer



Top of Sherman Granite

The elevations of the formation tops were all verified with hard data. Figure 6 is the updated 3D integrated model with the formation tops. This Petrel static model is exported to FEFLOW for further parameter estimation work. A new inversion method developed by our group is used to estimate boundary conditions for Casper Aquifer.

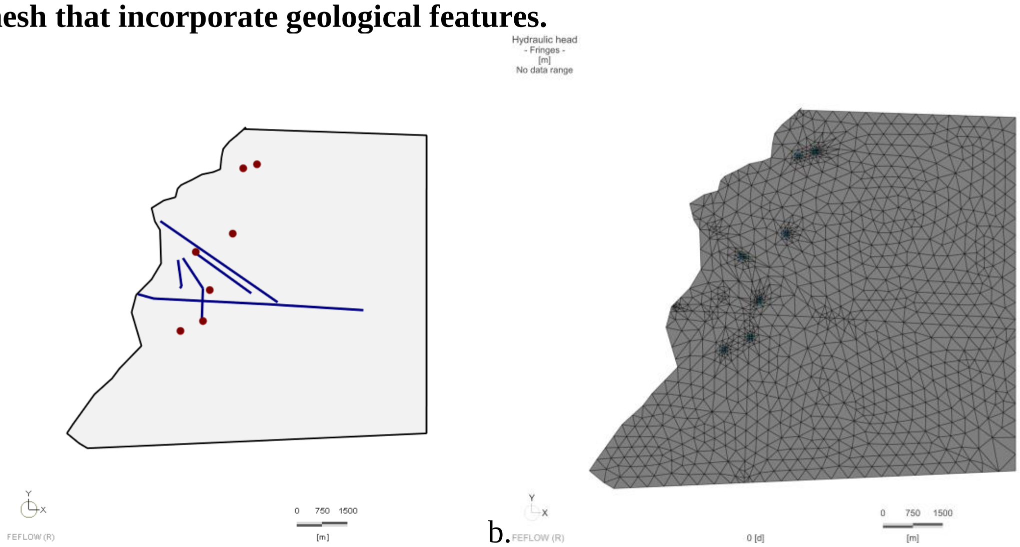
Figure 6: Updated 3D Petrel model with formation tops and location of the wells.



4.3 Parameter estimation

In 2016, it was proposed to use GWV for model calibration. However, after reviewing the capability of GWV, we've found that the dipping angle of Casper Aquifer is exceeding the calibration range of GWV, and it will give estimated parameters high error [7]. Thus, the model calibration work was performed using FEFLOW and FePEST instead of GWV and PEST. The Petrel structural model was imported to FEFLOW as a forward model. The FEFLOW model incorporates faults, well locations, three compartments (Lone Tree, Goose Creek, and Duck Creek), and tops of formations (Figure 7a). Finite element mesh was generated based on the locations of the geological features.

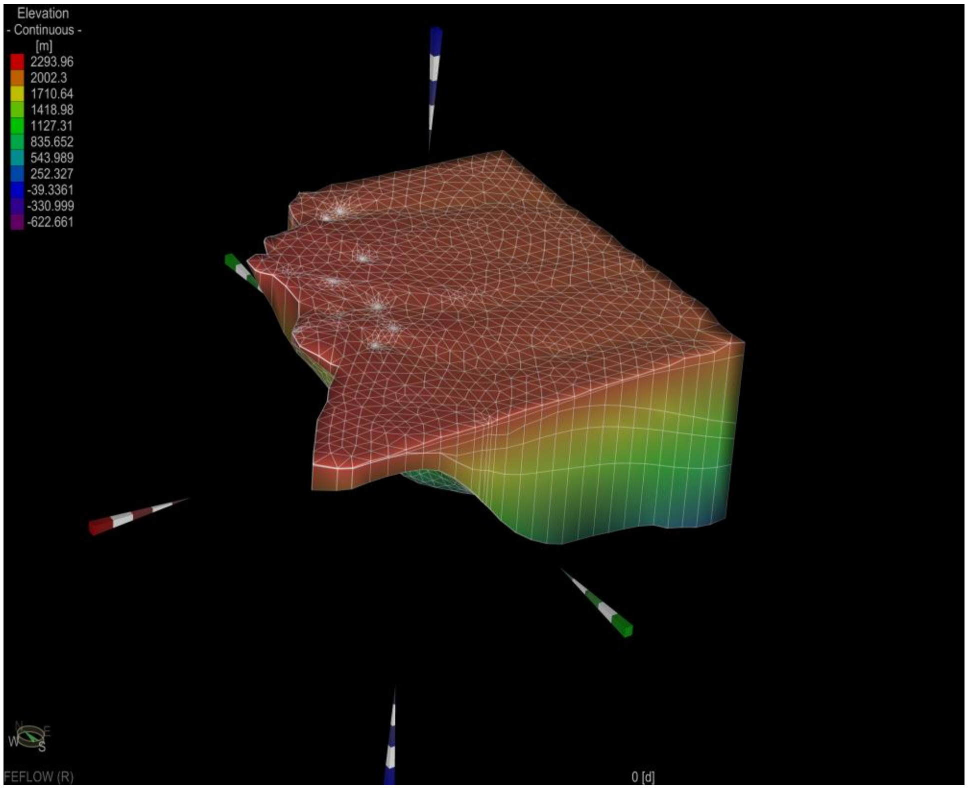
Figure 7: a. FEFLOW model with geological structures and well locations. b. Finite element mesh that incorporate geological features.



a. b.

After generating the mesh, elevation data of top and bottoms of the formations were imported to FEFLOW to give a 3D hydrostatic model (Figure 8).

Figure 8: 3D FEFLOW structural model.



__**Initial parameter estimations:**__

Previously, initial hydraulic parameter estimations were from 2012 Lidstone final report [1]. The estimations had been verified by using Aqtesolv with historic pumping data. Boundary conditions were roughly assigned to the model based on water level contour map from recent monitoring well data collection.

This year, new methods were also applied for hydraulic parameter and boundary condition estimation. Point-scale hydraulic conductivity values were estimated from core cuttings and well logs. Core cuttings are available for all wells except for Lone Tree Creek MON No. 1 well. For the 6 wells with core cuttings, a point-scale K (cm/s) was estimated using (results are shown in Table 1):

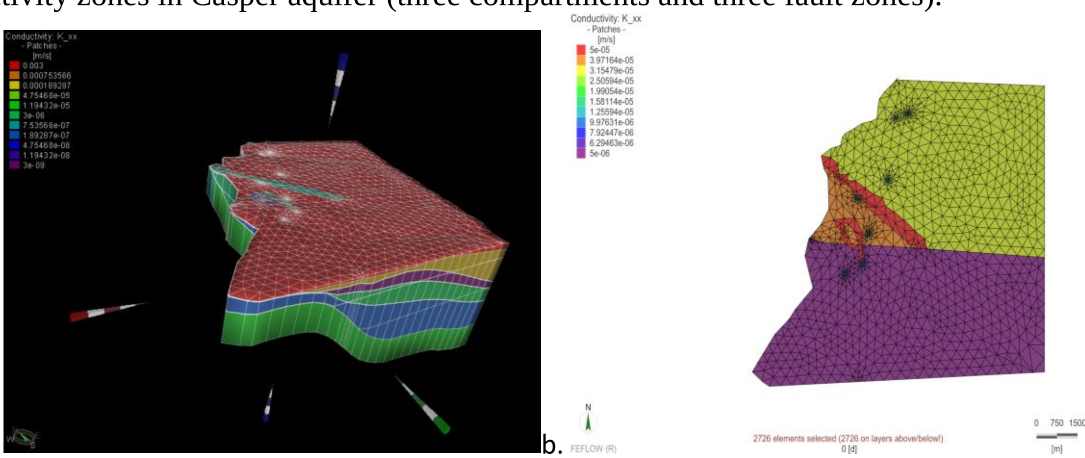
$$K = \frac{\delta_w g}{\mu} \cdot \frac{d^2}{180} \cdot \frac{\phi^3}{(1-\phi)^2}$$

Where d is diameter of the grain size (cm), which can be found from the cuttings using the grain size chart, δ_w denotes the fluid density ($\frac{g}{cm^3}$), μ is dynamic viscosity ($\frac{g}{cm \cdot s}$), and g is the acceleration of gravity which is 980 ($\frac{cm}{s^2}$).

Table 1: Calculated point-scale K from logging and cutting data in 6 wells.

	Corrected K ($\frac{gpd}{ft^2}$)
Lone Tree Fault MON No.1	N/A
Lone Tree #1	39.5
Lone Tree Fault 1-5	71.8
Lone Tree Fault 1-2	70.1
Goose Creek 2-2C	86.1
Duck Creek 3-1	9.8
Duck Creek #1	13.5

Hydraulic conductivity data from both Lidstone final report and point-scale estimation were assigned to FEFLOW model (Figure 9a). Figure 9b shows that there are six hydraulic conductivity zones in Casper aquifer (three compartments and three fault zones).



a. b.

Boundary conditions of the forward model were estimated using novel inverse methods with water level measurements in 2011(Table 2).

Table 2: Water levels of 6 wells in 2011.

	Lone Tree #1	Lone Tree Fault 1-5	Lone Tree Fault 1-2	Goose Creek 2-2C	Duck Creek 3-1	Duck Creek #1	LTC MON #1
Elevation (m)	2175.7	2228.3	2246.0	2198.1	2232.5	2204.2	2160.5
2011 Depth to Water (m)	19.5	64.2	102.8	74.7	125.7	67.9	
Water Level Elevation (m)	2156.2	2164.1	2143.2	2123.4	2106.8	2136.3	

A set of fundamental solutions of inversion is fitted locally to the observed water level and hydraulic conductivity, while flow continuity is honored over all inversion grid cells. The fundamental solutions of inversion are derived by solving the steady-state groundwater flow equation to obtain a set of local analytical solutions assuming that local K of a subdomain or a single inversion grid cell is homogeneous. However, unlike [3], whose fundamental solutions yielded only a single K value (i.e., ratios between facies K s were assumed known as a setoff prior information constraints for inversion), the fundamental solutions have been modified to allow the simultaneous estimation of both Ks of the reference model (this approach is extendable to any number of facies):

$$\tilde{h}(x,y) = a_o + a_1 x + a_2 y + a_3 xy + a_4(x^2 - y^2)$$
$$\tilde{q}_x(x,y) = -K(a_1 + a_3 y + 2a_4 x)$$
$$\tilde{q}_y(x,y) = -K(a_1 + a_3 x + 2a_4 y) \qquad (x,y) \in \Omega_i \qquad (2)$$

where $\tilde{h}$ denotes the approximate hydraulic head, ($\tilde{q}_x$, $\tilde{q}_y$) denote the approximate groundwater fluxes, a_i $(i = 0,\dots,4)$ denote a set of coefficients that locally define these approximate solutions, K is local hydraulic conductivity: $K \in (K_1; K_2, \dots)$ of the facie, and Ω_i is a subdomain of the problem, here corresponding to an inversion grid cell.

The continuity equations, which penalize the mismatch between the fundamental solutions at the interface between adjacent inversion grid cells, can be written as:

$$\delta\big(p_j(x_{,j}, y_j) - \epsilon\big)\Big(K_1\,\tilde{h}^{(k)}(x,y) - K_1\,\tilde{h}^{(l)}(x,y)\Big) = 0, \qquad \forall^{(k,l)} \in K_1$$

$$\delta\big(p_j(x_{,j}, y_j) - \epsilon\big)\Big(K_2\,\tilde{h}^{(k)}(x,y) - K_2\,\tilde{h}^{(l)}(x,y)\Big) = 0, \qquad \forall^{(k,l)} \in K_2$$

$$\delta\big(p_j(x_{,j}, y_j) - \epsilon\big)\Big(K_m\,\tilde{h}^{(k)}(x,y) - K_m\,\tilde{h}^{(l)}(x,y)\Big) = 0, \qquad \forall^{(k,l)} \in K_1 \in K_2\,, m \in (1,2)$$

$$\delta\big(p_j(x_{,j}, y_j) - \epsilon\big)\Big(\,\tilde{q}_n{}^{(k)}(x,y) - \,\tilde{q}_n{}^{(l)}(x,y)\Big) = 0, \qquad \forall\, K^{(k)} \neq K^{(l)}$$

$$\delta\big(p_j(x_{,j}, y_j) - \epsilon\big)\Big(\,\tilde{q}_t{}^{(k)}(x,y) - \,\tilde{q}_t{}^{(l)}(x,y)\Big) = 0,\ \forall\, K^{(k)} \neq K^{(l)} \quad (3)$$

where $p_j\big(x_{,j}, y_j\big)$ denotes the jth collocation point, which lies on the interface between grid cells (k) and (l), $\tilde{q}_n$ is normal flux at p_j, $\tilde{q}_t$ is tangential flux at p_j, $\delta\big(p_j(x_{,j}, y_j) - \epsilon\big)$ is a Dirac delta weighting function [3] that samples the mismatch between the fundamental solutions at $p_j\big(x_{,j}, y_j\big)$. The relation between $(\tilde{q}_n, \tilde{q}_t)$ and $(\tilde{q}_x, \tilde{q}_y)$ can be determined using the angles between the interface and the global coordinate axis.

Inversion further satisfies a set of data constraints which can be written as:

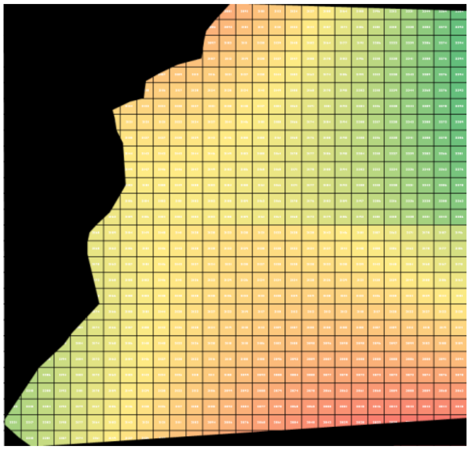
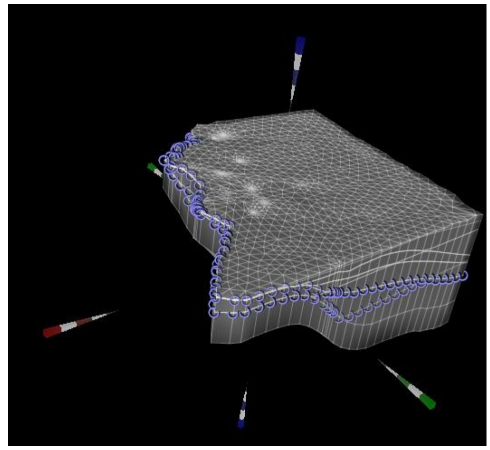
$$\delta(p_t - \epsilon)\Big(K_m\tilde{h}^{(k)}(x_t, y_t) - K_m h^o(x_t, y_t)\Big) = 0, \quad m \in (1,2)$$

$$\delta(p_t - \epsilon)\left(\tilde{h}_n{}^{(k)}(x_t, y_t) - h_n^o(x_t, y_t)\right) = 0$$

$$\delta(p_t - \epsilon)\left(\tilde{K}_n{}^{(k)}(x_t, y_t) - K_n^o(x_t, y_t)\right) = 0 \quad (4)$$

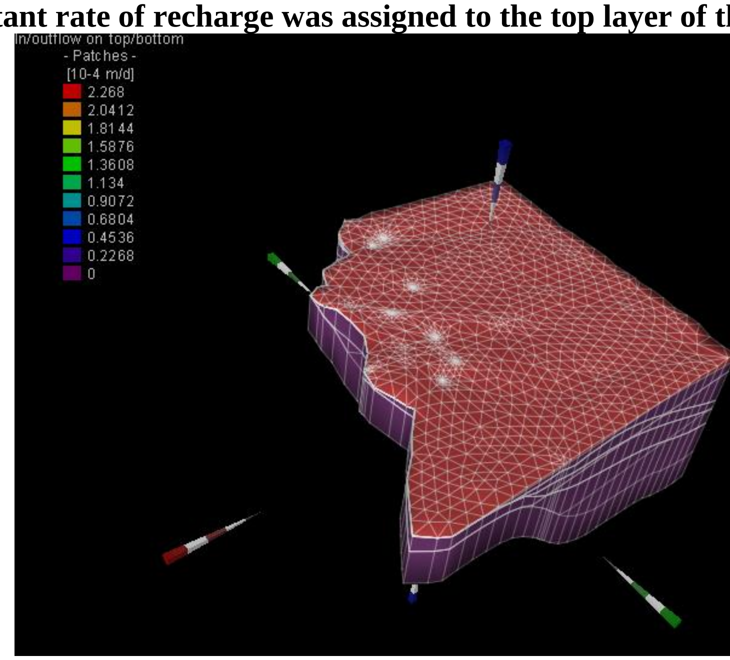
where $\delta(p_t - \epsilon)$is the Dirac delta weighting function, which reflects confidence in the observed data (e.g., it can be inversely proportional to the measurement error variance), (x_t, y_t) represents the location where an observed datum was sampled, and h^o, K^o are the observations, K_m denotes the conductivity of the facies which contains the observations. If the flux measurements exist, they will be used here to provide flow rate related information for inversion because conductivity cannot be uniquely identified from hydraulic head observations alone. If subsurface flow rate measurements are available, the flux conditioning equations can be integrated to enforce conditioning by flow rates [3]. In Belvoir Ranch, neither flux or flow rate data are available, thus only head and local conductivity data were used for inversion. The inverted head map using 2011 water level data is shown in Figure 10a. The boundary conditions along the ranch boarders are assigned to FEFLOW forward model (Figure 10b).

Figure 10: a. Inverted head map using the novel inverse method. b. FEFLOW model with boundary conditions.

a.  b. 

Besides boundary conditions of Belvoir Ranch, an averaged annually natural recharge rate had been assigned to the top layer of the model. According to [8], annual precipitation rate of Cheyenne is 16 inches, and about 22% of the precipitation goes into underground [9], thus a constant value of recharge rate of 2.27e-4 m/d was assigned to the Model (Figure 11).

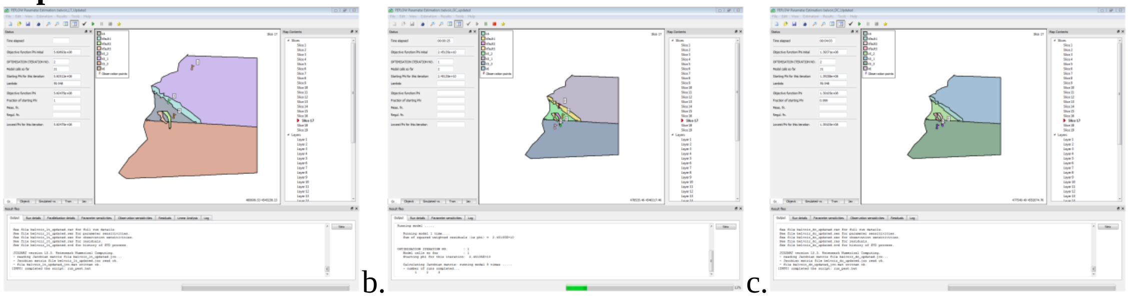
Figure 11: A constant rate of recharge was assigned to the top layer of the model.



<u>Parameter estimation with FEFLOW-PEST</u>

In 2011, there were three pumping events in the ranch, and were performed for each compartment at a time. Water level data of the pumping well and observation wells from each of the pumping test were imported to FEFLOW for parameter estimation (Figure 12).

Figure 12: FEFLOW model of Lone Tree Creek(a), Goose Creek(b), and Duck Creek(c) compartment.



a. b. c.

Hydraulic conductivities of Goose Egg Formation, three faults, three compartments of Casper Aquifer, and Sherman Granite were calibrated for each pumping test. The results of the three pumping test calibrations are shown in Table 3. Highlighted cells represents for the estimated values that will be used to calculate a value for an integrated model. Estimated parameters were used in a forward model for further analysis.

Table 3: FEFLOW hydraulic conductivity estimation results.

Pumping Well	**Lone Tree Fault 1-5**	**Duck Creek 3-1**	**Goose Creek 2-2C**	**Estimated Parameters (m/s)**
Observation Wells	Lone Tree No.1, Lone Tree Creek 1-2, Goose Creek 2-2C	Duck Creek No.1	Duck Creek 3-1, Lone Tree Fault 1-2, Duck Creek No.1	
Goose Egg Formation	6.18E-06	4.61E-06	1.07E-06	3.95E-06
Fault No.1	1.06E-07	1.05E-05	3.44E-05	1.06E-07
Fault No.2	1.62E-06	1.67E-06	1.96E-06	1.81E-06
Fault No.3	1.55E-06	1.58E-06	1.63E-06	1.61E-06
Lone Tree Creek Compartment	4.43E-04	3.87E-04	1.30E-04	4.43E-04
Goose Creek Compartment	1.98E-07	2.28E-06	1.44E-07	2.28E-06
Duck Creek Compartment	1.02E-07	8.09E-08	1.66E-07	1.66E-07
Sherman Granite	8.74E-06	7.55E-06	1.26E-06	5.85E-06

By incorporating geophysical and borehole data at the Ranch, a 3D aquifer model was built. Aquifer boundary conditions in April 2016, inverted using the new inverse method, were imported to the model, the assumption being that the radial cone of depression from the pumping program will not reach the actual boundaries. This assumption, however, will be subject to revision. The calibrated hydraulic conductivity values, also obtained from inversion, were assigned to the Casper Aquifer layers in the 3D model. The 3D model was first run under steady state flow with zero pumping rates for all wells. The simulated water level and observed water level are compared. The percentage errors of the simulated heads of all wells are within +/-4%.

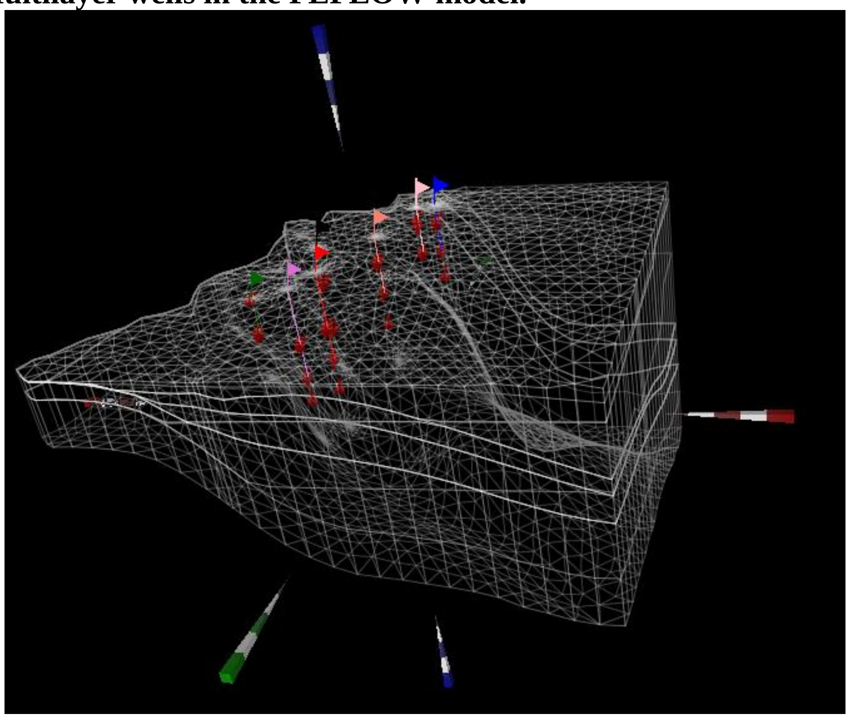
Table 4: Comparison between simulated heads and true heads in 6 wells (Lone Tree MON #1 is a monitoring well).

	True heads (m)	Simulated heads (m)	%error
LT1	2180.8	2114.3	3.15%
LT15	2192.7	2134.8	2.71%
LT12	2176.1	2161.9	0.66%
GC22C	2149.2	2156.1	0.32%
DC31	2140.3	2156.9	0.77%
DC1	2193.9	2167.4	1.22%

4.4 Pumping Modeling

The same 3D model is run under transient mode where multilayer production wells were assigned to the six well locations (Figure 13). Since Lone Tree MON#1 is an observation well, it will not be used during production well design.

Figure 13: Multilayer wells in the FEFLOW model.



Different combinations of production rates and well rotations were simulated. In order to obtain a sustainable status for water supply, a minimum hydraulic head constraint was set to be the top of the Casper Aquifer at all well locations thus the Casper Aquifer will be under confined condition.

In the first case, a set of target pumping rates were used based on recommendation from [1]. The pumping rates were assigned to all wells, and the simulation results are shown in Table 5. Water level in Duck Creek No.1 Well drops under the minimum water level constraint, thus, Duck Creek No.1 is not suggested to be used as production well even with a relatively small production rate. All wells in Lone Tree Compartment have good potentials to produce.

Table 5: Suggested pumping rate from [1] and simulation results when all wells are pumping using the suggested rate.

	Production rate (gpm)	Minimum water level constraint	Simulated water level
LT1	600	1981.5	2114.05
LT15	600	1935.6	2134.42
LT12	600	1832.4	2142.87
GC22C	100	1556.1	2151.76
DC31	200	1619.7	2144.18
DC1	200	2196.2	2152.18

In the second case, all wells were pumped separately with high production rate (1000 gpm) for 5 years. Water levels of wells in Lone Tree Creek Compartment do not have significant change. In Goose Creek Compartment, water level drops 27 meters in Goose Creek 2-2C. In Duck Creek Compartment, water levels in two wells drop the most comparing to other wells (Table 6).

Table 6: Simulation results for separately pumping events with high production rate.

	Production rate (gpm)	Minimum water level constraint	Simulated water level	Water Level Difference (m)
LT1	1000	1981.5	2114	0.3
LT15	1000	1935.6	2134	0.8
LT12	1000	1832.4	2161	0.9
GC22C	1000	1556.1	2129	27.1
DC31	1000	1619.7	2099	57.9
DC1	1000	2196.2	2096	71.4

In the third case, Lone Tree Fault No.1 and Lone Tree Fault 1-5 wells were pumped simultaneously with production rate of 4000 gpm for 5 years. Water level is not dropping significantly (Table 7).

Table 7: Simulation results for simultaneous pumping events with high production rate for Lone Tree Fault No.1 and Lone Tree Fault 1-5 wells.

	Production rate (gpm)	Minimum water level constraint (m)	Simulated water level (m)	Water Level Difference (m)
LT1	4000	1981.5	2112	2.3
LT15	4000	1935.6	2133	1.8

Based on the above results, candidate wells are the three wells in Lone Tree Creek Compartment. Besides water level, sand production is another factor that needs to be considered for production wells (Table 8). Among three wells in Lone Tree Compartment, Lone Tree 1-5 has the smallest sand production, thus Lone Tree 1-5 is the best candidate for water production.

Table 8: Sand production rates for 4 wells.

	Sand Production (ppm)
LT1	0.37/0.07
LT15	Trace
LT12	
GC22C	0.01
DC31	0.56
DC1	

Pumping Program:

Based on flow simulation using the 3D groundwater models, a pumping plan has been designed (Table 9), where individual well production rate is selected based on the well capacity and historic precipitation data (Figure 2). Lone Tree Fault No.1 and Lone Tree Fault 1-5 are the two main wells that can be used for water production. This pumping program, however, will be affected by specific precipitation of the year (i.e., future climate condition) and other factors such as sand production.

Table 9: Pumping program for 6 wells in a year.

Pumping Rate	January	February	March	April	May	June	July	August	September	October	November	December
LT1	1000	1000	2000	2000	3000	3000	3000	3000	2000	2000	1000	1000
LT15	1000	1000	2000	2000	3000	3000	3000	3000	2000	2000	1000	1000
LT12	800	800	1500	1500	2000	2000	2000	2000	1500	1500	800	800
GC22C	-	-	200	200	200	200	200	200	200	200	200	-
DC31	-	-	500	500	500	500	500	500	500	500	500	-
DC1	-	-	-	-	-	-	-	-	-	-	-	-

5 Conclusion & Significance

Using a new inverse theory, this research first calibrated a 2D groundwater model for the Casper Aquifer in Belvoir Ranch with sparse hydrological observations. The new theory enables the joint estimation of aquifer hydraulic conductivities and boundary conditions under steady state flow. Water levels of 7 wells in April 2016 were used to condition the inversion, when water levels in all wells were relatively stable compared to other months. By incorporating geophysical and borehole data at the Belvoir Ranch, a 3D aquifer model was built next. Aquifer boundary conditions in April 2016, inverted using the new inverse method, were imported to the model, the assumption being that the radial cone of depression from the pumping program will not reach the actual boundaries. The calibrated hydraulic conductivity values, also obtained from steady-state inversion, were assigned to the Casper Aquifer layers in the 3D model. For the 3D model, hydraulic parameters of multiple hydrogeological units (including the Casper Aquifer) were further calibrated using pumping tests data from 2011. With this model, various design pumping programs (pumping rates and well rotations) were simulated. To select water supply wells among the current 6 test wells, the recommended aquifer compartment is the Lone Tree Compartment of the Casper Aquifer. Lone Tree Compartment not only has the highest hydraulic conductivity, it can also capture the natural recharge into the subsurface from the Lone Tree Fault. Moreover, uncertainties in the model have been reduced using the following strategies: (1) To reduce uncertainty of aquifer

K distribution, the model was divided into zones given the observed geological data, and an equivalent *K* was estimated for each zone to represent small-scale heterogeneity not incorporated in model. The equivalent *Ks* were calibrated using both steady state inversion and transient pumping test data; (2) To reduce uncertainty of location, timing, and rate of aquifer recharge, a recharge layer was assigned on the top of the model during both parameter calibration and simulation; (3) To reduce the uncertainty of aquifer boundary conditions, the novel inverse method was used to invert the likely aquifer boundary conditions. Overall, this study has successfully reduced uncertainties in the model, and gives predicted water level responses for future production programs. This research also marks the first successful application of a new groundwater inverse method where aquifer hydraulic parameters and boundary conditions are jointly estimated.

Publications & Presentations:

Fangyu Gao†, Ye Zhang (2018) An inverse method for the simultaneous estimation of aquifer thickness, hydraulic conductivities, and boundary conditions using borehole and hydrodynamic data, Journal of Hydrology, in preparation.

Fangyu Gao†, Ye Zhang (2017) Simultaneous estimation of aquifer thickness, conductivity, and BC using borehole and hydrodynamic data with geostatistical inverse direct method, AGU Annual Meeting, New Orleans, Louisiana, poster presentation.

Fangyu Gao†, Ye Zhang (2017) Applying spectral data analysis techniques to infer aquifer properties in Belvoir Ranch, Wyoming, AGU Annual Meeting, New Orleans, Louisiana, poster presentation.

Fangyu Gao†, Ye Zhang (2017) A new inverse method for the simultaneous estimation of aquifer thickness and boundary conditions based on borehole and hydrodynamic measurements, AGU Hydro Days, Fort Collins, CO, March 20 – 22, 2017, oral presentation.

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One student, Miss Fangyu Gao, has been funded by this project since September 2015. Miss Gao received her B.S. and M.S. in Petroleum Engineering from the Colorado School of Mine. She is currently a 3nd year Ph.D. candidate in the Program of Hydrology at the Department of Geology & Geophysics, University of Wyoming. She has successfully completed her Ph.D. Qualifying and Ph.D. Preliminary Exam during the Fall semester of 2016 and Spring semester of 2018. Fangyu is currently writing up her research outcomes in the form of two journal articles.

Conferences Attended:

AGU Annual Meeting, 2016;
AGU Hydrology Days, 2017;
AGU Annual Meeting, 2017.

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A New Multifunctional Sorbent for the Treatment of Coproduced Waters from the Energy Industry

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2. Maryam Irani, Andrew T. Jacobson, Khaled A.M. Gasem, Maohong Fan, Modified Carbon Nanotubes/Tetraethylenepentamine for CO2 Capture, Fuel 206 (2017) 10–18.

A NEW MULTIFUNCTIONAL SORBENT FOR THE TREATMENT OF COPRODUCED WATERS (CWS) FROM THE ENERGY INDUSTRY

Final report

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Abstract

Large tracts of Wyoming farmland contain high concentrations of CO_3^{2-} and HCO_3^-. Since these could lead to significant environmental issues such as the reduced availability of micronutrients for plants, coproduced waters (CWs) high in CO_3^{2-} and HCO_3^- cannot be used directly for irrigation in Wyoming. CWs must therefore be treated prior to application, which is a very challenging issue currently facing the fossil fuel production industry. Reducing CO_3^{2-} and HCO_3^-—and thus salinity and alkalinity in CWs—would significantly benefit not only agriculture, but energy development in Wyoming as well.

The proposed project seeked to develop a new technology for the on-farm or on-site reduction of salinity and alkalinity to lower carbonate (CO_3^{2-}) and bicarbonate (HCO_3^-) from CWs discharged from the energy industry, thus protecting water and soil resources. The purpose and specific goals of the project are to reduce total concentrations of CO_3^{2-} and HCO_3^- in discharged CWs by 90% at a lower cost per metric ton than other commercially available technologies. The project seeks to achieve these goals through the use of recently developed and commercially available $TiO(OH)_2$ to remove carbonate (CO_3^{2-}) and bicarbonate (HCO_3^-) in the CWs discharged from oil and gas wells (e.g., wells operated by EOG Resources Inc. and Chesapeake Energy) and oil refining companies (e.g., HollyFrontier, a company currently collaborating with Dr. Fan's group at UW). It should be noted that $TiO(OH)_2$ is different in structure from conventional crystal anatase TiO_2 and $Ti(OH)_2$. The $TiO(OH)_2$ to be used in the proposed project has an amorphous structure, which makes the material highly capable for adsorption. Also, as a high-capacity sorbent, $TiO(OH)_2$ can remove not only CO_3^{2-} and HCO_3^- but other contaminants such as heavy metals [e.g., arsenic (As), selenium (Se), and lead (Pb)] as well.

The project will be realized by demonstrating the proposed CWs remediation technology in pilot-scale applications either at an oil well site of EOG Resources Inc. or a HollyFrontier refinery in Wyoming. Because the high salinity and alkalinity of CWs contaminated with CO_3^{2-} and HCO_3^- degrade water and soil resources needed by farmers for agricultural production, the success of the proposed technology will directly benefit all Wyoming agricultural producers.

1. Objectives

Large tracts of Wyoming farmland contain high concentrations of CO_3^{2-} and HCO_3^-. Since these could lead to significant environmental issues such as the reduced availability of micronutrients for plants, coproduced waters (CWs) high in CO_3^{2-} and HCO_3^- cannot be used directly for irrigation in Wyoming. CWs must therefore be treated prior to application, which is a very challenging issue currently facing the fossil fuel production industry. Reducing CO_3^{2-} and HCO_3^-—and thus salinity and alkalinity in CWs—can significantly benefit not only agriculture, but energy development in Wyoming as well.

The project was designed to develop a new technology for the on-farm or on-site reduction of salinity and alkalinity to lower carbonate (CO_3^{2-}) and bicarbonate (HCO_3^-) from CWs discharged from the energy industry, thus protecting water and soil resources. The purpose and specific goals of the project are to reduce total concentrations of CO_3^{2-} and HCO_3^- in discharged CWs by 90% at a lower cost per metric ton than other commercially available technologies. The project seeks to achieve these goals by using recently developed and commercially available $TiO(OH)_2$ to remove carbonate (CO_3^{2-}) and bicarbonate (HCO_3^-) in the CWs discharged from oil and gas wells (e.g., wells operated by EOG Resources Inc. and Chesapeake Energy) and oil refining companies (e.g., HollyFrontier, a company currently collaborating with Dr. Fan's group at UW). It should be noted that $TiO(OH)_2$ is different in structure from conventional crystal anatase TiO_2 and $Ti(OH)_2$. The $TiO(OH)_2$ used in the proposed project has an amorphous structure, which makes the material highly capable for adsorption. Also, as a high-capacity sorbent, $TiO(OH)_2$ can remove not only CO_3^{2-} and HCO_3^- but other contaminants such as heavy metals [e.g., arsenic (As), selenium (Se), and lead (Pb)] as well.

2. Significance and Background

2.1 Related Research

Due to the continuous growth of population and industry in Wyoming, developing and securing clean water resources is one of the major challenges we face in the 21st century. Surface water will still be available to meet various future needs, but rapid economic development in our state may lead to the depletion of these resources. Therefore, other water resources must be developed.

The CWs from various energy production industries (coal, natural or shale gas, and oil) [1, 2] are considered to be important potential new water resources. However, many of these must be treated due to their quality issues, especially high CO_3^{2-} and HCO_3^- levels [2, 3]. Removal of CO_3^{2-} and HCO_3^- from CWs can significantly improve their application in agriculture.

Many methods, including membrane and reverse osmosis [4-6], have been studied either to remove CO_3^{2-} and HCO_3^- or at least lower their concentrations to allowable levels, while adsorption is the most promising method due to its effectiveness and simplicity for point-of-use applications. A search of the literature shows that very little attention has been paid to the adsorption of carbonate and bicarbonate anions by adsorbents. In 1993, L. Zang *et al.* studied the possibility of the adsorption of carbonate and bicarbonate anions on colloidal silver particles [6, 7]. However, using this type of adsorbent for removal of CO_3^{2-} and HCO_3^- is not practical.

Therefore, although their development is challenging, simple and cost-effective methods for removing CO_3^{2-} and HCO_3^- in CWs are worth pursuing. The proposed $TiO(OH)_2$-based method is designed to overcome the shortcomings of the abovementioned methods and to fill a gap in the area of CWs treatment.

2.2 Wyoming Water

It is well known that Wyoming is a semi-arid region in the U.S. Accordingly, Wyoming has limited sustainable surface water resources, and though they occasionally swell to very high levels, rivers and streams in the state have little flow. Moreover, natural disasters such as droughts and tornadoes unpredictably plague regions of Wyoming, undermining agricultural and industrial productivity and adversely affecting the well-being and social fabric of communities. For instance, 2012 was the driest of the last 118 years, which led to the lowest hay crop yield since 2002 [8]. Further, the contamination of waterways from human activity may further weaken Wyoming's ability to meet its water needs. Therefore, Wyoming must be prepared to meet the threat of potential water shortages. To address this crisis and its associated challenges, Wyoming statute Title 35, Chapter 11, Article 3 (35-11-309) declares that “water is one of Wyoming’s most important natural resources, and the protection, development and management of Wyoming’s water resources is essential for the long-term public health, safety, general welfare and economic security of Wyoming and its citizens.”

Meanwhile, the mining and energy production industries in Wyoming generate a great amount of coproduced waters (CWs). It is common knowledge that these CWs have high concentrations of CO_3^{2-} and HCO_3^-. Given that many of Wyoming’s soil and water resources already contain high concentrations of CO_3^{2-} and HCO_3^-, the disposal of CWs therefore not only further diminishes the quality of these resources, but also wastes highly valuable water resources the state sorely needs. For these reasons, the treatment and recycling of CWs in Wyoming is a win-win strategy for our state. However, conventional treatment methods need either expensive or multi-step methods to remove CO_3^{2-} and HCO_3^- from CWs. The shortcomings of the multi-step methods are obvious, and are not only expensive but can sometimes lead to secondary contamination as well. To overcome these shortcomings, we have made efforts to develop a simple, multifunctional technology for the simultaneous removal of CO_3^{2-} and HCO_3^- to improve the overall quality of CWs, thus providing an inexpensive and reliable water resource for Wyoming.

3. Methodology

3.1. Experimental/Procedure

The $TiO(OH)_2$ powders were synthesized from thermal decomposition of titanium isopropoxide, $Ti(O\text{-}iC_3H_7)_4$, in water, at room temperature as seen in Reaction 1.

$$Ti(O\text{-}iC_3H_7)_4 + 4H_2O \rightleftharpoons TiO(OH)_2 + 4C_3H_7OH + H_2O \quad \text{R1}$$

The first step was to add a predetermined amount of $Ti(O\text{-}iC_3H_7)_4$to DI water with the molar ratio of H_2O: $Ti(O\text{-}iC_3H_7)_4$ being 27.6:1, followed by stirring the resultant mixture for 4 hours. The gel preparation process started when both solutions were mixed together under constant stirring. The precipitate $TiO(OH)_2$ was then filtered, rinsed two times with DI water and ethanol, then was dried at 100 °C overnight.

The adsorption experiments were then carried out in three one liter batch reactors, each equipped with a mechanical stirrer. Each reactor had an argon flow connection to clear the reactor head space of CO_2, controlled by flow controllers. All experiments completed were run at least three times for statistical analysis. For the experiments, a predetermined amount of $NaHCO_3$ and/or Na_2CO_3 was added to one liter of DI water in each reactor. This was followed by the addition of a set amount of $TiO(OH)_2$. All reactions were run for 30 hours to guarantee equilibrium was reached. Samples were taken throughout this time for analysis of the bicarbonate and carbonate concentrations left in the water. A picture of the reactor set-ups can be seen in Figure 2.

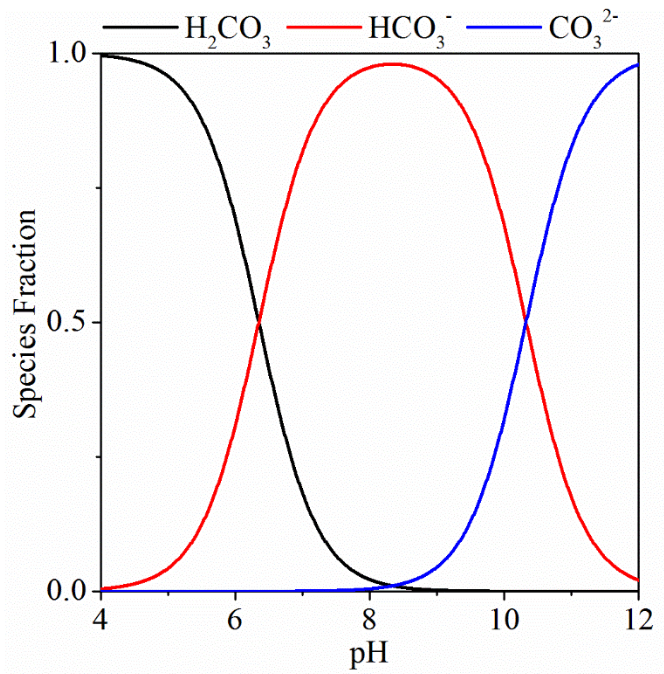

Fig. 1 The speciation fraction dependace of aqueous carbonate with pH

Sets of adsorption experiments (varying initial adsorbate concentrations) completed at one of three pH values. The completed set was at a pH of 8.2 where bicarbonate is the major species present. The set at a pH~10 where the species is a mix of carbonate and bicarbonate, and at a pH of 11 where the main species present is carbonate are to be performed. The speciation with pH can be seen in Figure 1. The first set of experiments (pH=8.2) has had kinetic and isotherm modeling applied.

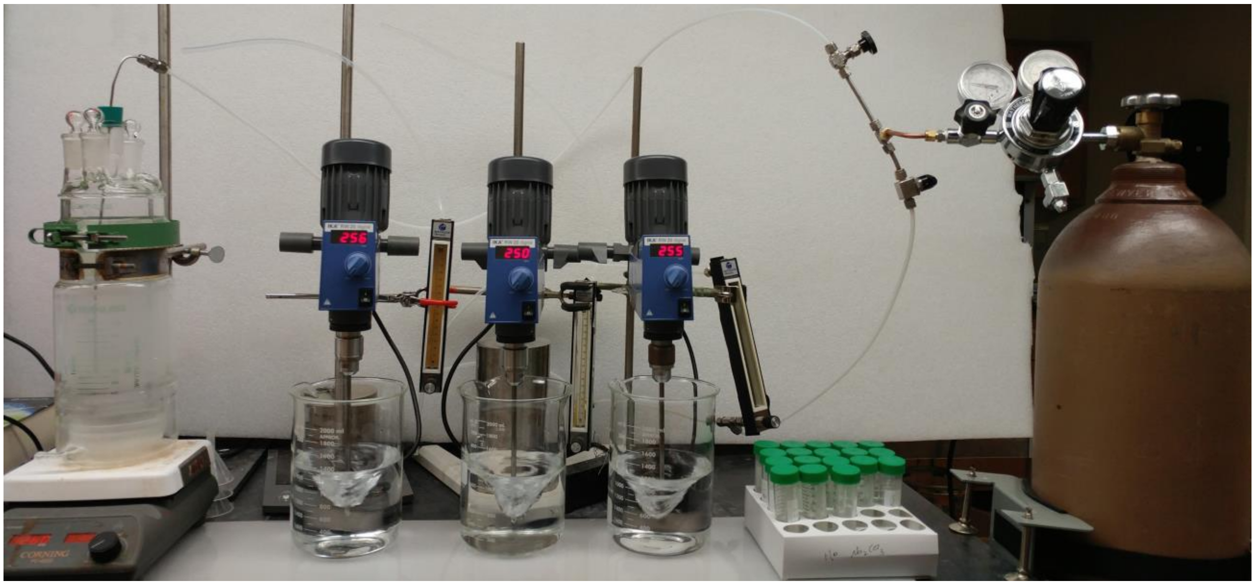

Fig. 2 Experimental set up for carbonate adsorption

3.2 Instrumentation

For aqueous carbonate/bicarbonate analysis, an SI Analytics Titroline 6000 autotitrator along with a Shimadzu total carbon analyzer was used. C13 nuclear magnetic resonance (NMR) analysis was completed at the University of Colorado in Boulder. Elemental analysis was completed with a PerkinElmer NexION 300S ICP-MS inductively coupled plasma mass spectrometer (ICP-MS). An FEI Quanta FEG 450 field-emission scanning electron microscope (SEM) was used to image $TiO(OH)_2$. A Nicolet/iS50 Fourier transform infrared (FTIR) spectrometer was used for structure analysis. Thermogravimetric analysis (TGA) of $TiO(OH)_2$ was performed using a TA Instruments SDT Q600 TGA. A Rigaku Smartlab X-ray diffraction system using a Cu Kα1 line (1.5406 Å) operating at 40 kV/40 mA, with 2θ ranging from 10° to 90° was used for the X-ray diffraction (XRD) analysis. The BET (Brunauer-Emmett-Teller) surface area and BJH (Barrett-Joyner-Halenda) pore volume were acquired using a Quantachrome Autosorb IQ automated gas sorption analyser.

3.3 Kinetic Theory

The kinetic models of CO_3^{2-} and HCO_3^- sorption are needed for designing pilot-scale and, eventually, industrial-scale demonstrations of the proposed technology. The kinetic rate equation is expressed as [9, 10]:

$$\frac{dq_t}{dt} = k(q_{eq} - q_t)^2 \qquad \text{(E1)}$$

where k [g-TiO(OH)$_2$/(mg-HCO_3^-.h) or -TiO(OH)$_2$/(mg-HCO_3^-.h)] represents the pseudo-second-order rate constant of CO_3^{2-} and HCO_3^- sorption. By integrating E1 with the boundary condition of $q_{t=0} = 0$, the following linear equations can be obtained:

$$\frac{1}{q_{eq} - q_t} = \frac{1}{q_{eq}} + kt \qquad \text{(E2)}$$

or

$$\frac{t}{q_t} = \frac{1}{q_{eq}}t + \frac{1}{V_0} \qquad \text{(E3)}$$

$$V_0 = kq_{eq}^2 \qquad \text{(E4)}$$

where V_0 [mg- HCO_3^-/(g-TiO(OH)$_2$ h)] is the initial sorption rate. The q_{eq} in E4 can be derived using the slope of t/q_t vs. t, while k in E4 can be determined using the slope of $1/(q_{eq} - q_t) \sim t$.

3.4 Isotherm Theory

The adsorption isotherm for bicarbonate adsorption was characterized using four models; Langmuir, Freundlich, Dubinin-Rasushkevich (D-R), and Redlich-Peterson (R-P) [11]. The Langmuir model can be expressed as:

$$q_e = \frac{q_m bC_e}{1 + bC_e} \qquad \text{(E5)}$$

or in linear form:

$$\frac{C_e}{q_e} = \frac{1}{bq_m} + \frac{C_e}{q_m} \tag{E6}$$

where q_e (mg g^{-1}) is the equilibrium adsorbed concentration, C_e (mg L^{-1}) is the adsorbate equilibrium concentration in solution, q_m (mg g^{-1}) is the maximum monolayer coverage capacity, and b (L mg^{-1}) is the equilibrium adsorption constant. The Freundlich isotherm model in its non-linear (E8) and linear (E9) forms are as follows:

$$q_e = K_f C_e^{\frac{1}{n}} \tag{E8}$$

$$\ln(q_e) = \ln(K_f) + \frac{1}{n}\ln(C_e) \tag{E9}$$

with K_f (mg g^{-1}) being the Freundlich isotherm constant and n the adsorption intensity. Unlike Langmuir, the Fruendlich isotherm is not restricted to the formation of a monolayer. The nonlinear (E10) and linear (E11) forms of the Dubinin-Rasushkevich (D-R) isotherm model are expressed as:

$$q_e = q_s e^{-k_{ad}\varepsilon^2} \tag{E10}$$

$$\ln(q_e) = \ln(q_s) - k_{ad}\varepsilon^2 \tag{E11}$$

where q_s (mg g^{-1}) is the isotherm saturation capacity, and k_{ad} (mol^2 kJ^{-2}) and ε are the Dubinin-Rasushkevich isotherm constants with ε equal to:

$$\varepsilon = RT\ln(1 + \frac{1}{C_e}) \tag{E12}$$

where R is the gas constant and T the absolute temperature (K). Last the Redlich-Peterson (R-P) three parameter isotherm model was applied. The R-P model is a combination of the Langmuir and Fruendlich isotherm models. It is expressed as:

$$q_e = \frac{K_r C_e}{1 + a_r C_e^g} \tag{E5}$$

with K_r (L/g) and a_r (mg^{-1}) are the R–P isotherm constants, and g is the R-P isotherm exponent.

4. Principal Findings

4.1 $TiO(OH)_2$ Characterization

Thermogravimetric Analysis (TGA)

For TGA analysis $TiO(OH)_2$ was heated at 20 °C /min up to 1000 °C. Only data up to 600 °C is shown in Figure 3 as there were no changes above this temperature. It was expected to see the evaporation of physically adsorbed water at around 100ºC. Thermal decomposition of the $TiO(OH)_2$ started around 300 °C, which is much higher than needed for bicarbonate/carbonate adsorption. The $TiO(OH)_2$ had a total weight loss of about 20 wt.% after decomposition.

Scanning Electron Microscopy

The SEM images in Figure 4 show the porous structure of $TiO(OH)_2$ important for reaction sites in the removal of carbonate and bicarbonate.

Fourier Transform Infrared Spectroscopy (FTIR)

The Fourier transform infrared spectroscopy (FTIR) spectra collected for $TiO(OH)_2$ can be seen in Figure 5. The FTIR spectrum of fresh $TiO(OH)_2$ shows a characteristic peak in 400-900 cm^{-1} range, which can be attributed Ti–O stretching vibrations. The additional peak at 1000-1700 cm^{-1} range can be attributed to Ti-O-H bonds, while the broad peak in the 2500-3500 cm^{-1} range corresponds to the small amount of water adsorbed on the surface of $TiO(OH)_2$.

X-ray diffraction (XRD)

X-ray diffraction (XRD) data for pure $TiO(OH)_2$ can be seen in Figure 6. It is clear that the $TiO(OH)_2$ is an amorphous material. The three broad peaks at 30, 45, and 60 2θ can be assigned to small amount of titanium dioxide being present in the material. This TiO_2 is likely formed during $TiO(OH)_2$ preparation.

Brunauer-Emmet and Teller (BET) Analysis

Brunauer-Emmet and Teller analysis (BET) was used to study the surface area and pore size/volume of the prepared $TiO(OH)_2$ sample. This data can be seen in Table 1. The high surface area of $TiO(OH)_2$ is beneficial for the adsorption of bicarbonate/carbonate.

Solid Carbon-13 Nuclear Magnetic Resonance (NMR) Analysis

C13 NMR analysis was completed to show the adsorption of carbonate onto $TiO(OH)_2$. This analysis is shown in Figure 7. The samples were analyzed before and after adsorption experiments. The large peak at ~115 ppm is due to the background and Teflon rotor because of single pulse analysis. The small peak at 167 ppm can be seen only in the $TiO(OH)_2$ after adsorption. This peak can be attributed to carbonate adsorbed to the surface.

Table 1 BET data for $TiO(OH)_2$ including surface area, pore volume, and pore size

BET data for $TiO(OH)_2$			
Sample	Surface Area (m^2/g)	Pore Volume (cm^3/g)	Pore Size (A^o)
Fresh $TiO(OH)_2$	672.16	0.461	32.97

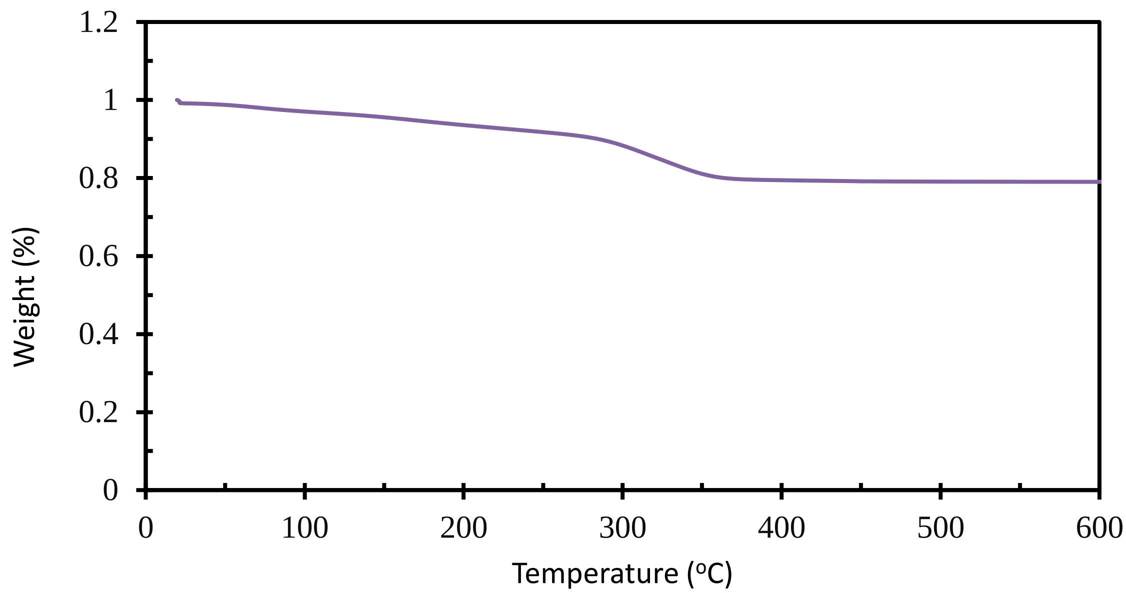

Fig. 3 TGA of $TiO(OH)_2$ [TGA conditions: heated at 20.00 °C/min to 1000.00 °C, the data above 600°C shows no change, N_2 flow = 0.1 L/min

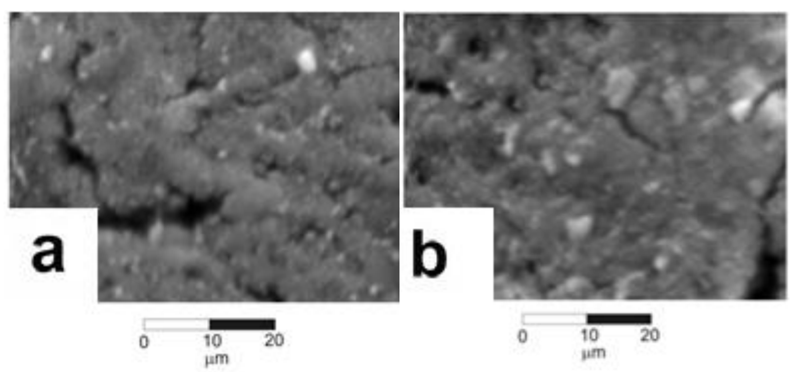

Fig. 4 SEM images of $TiO(OH)_2$

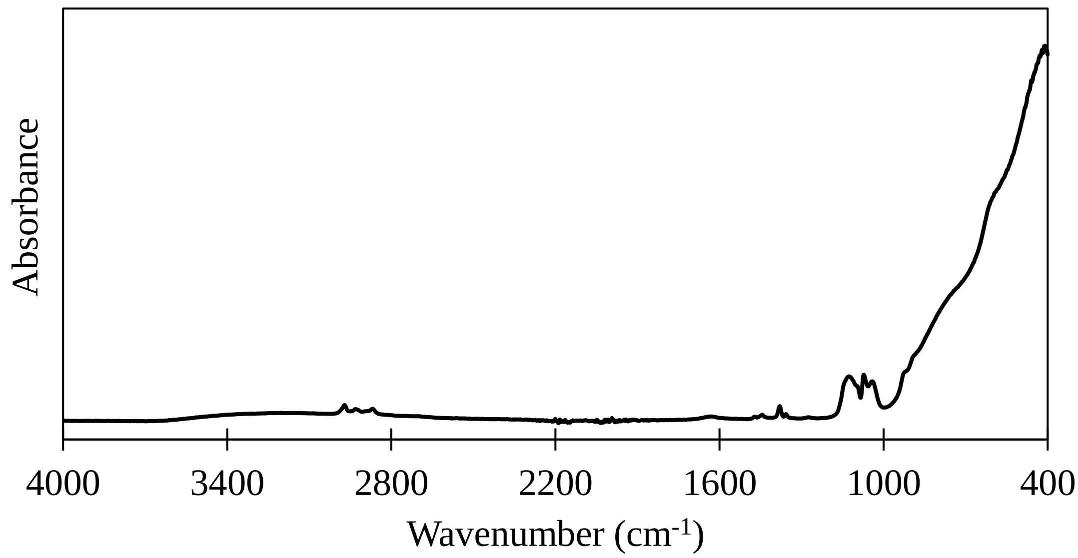

Fig. 5 FT-IR spectra of $TiO(OH)_2$

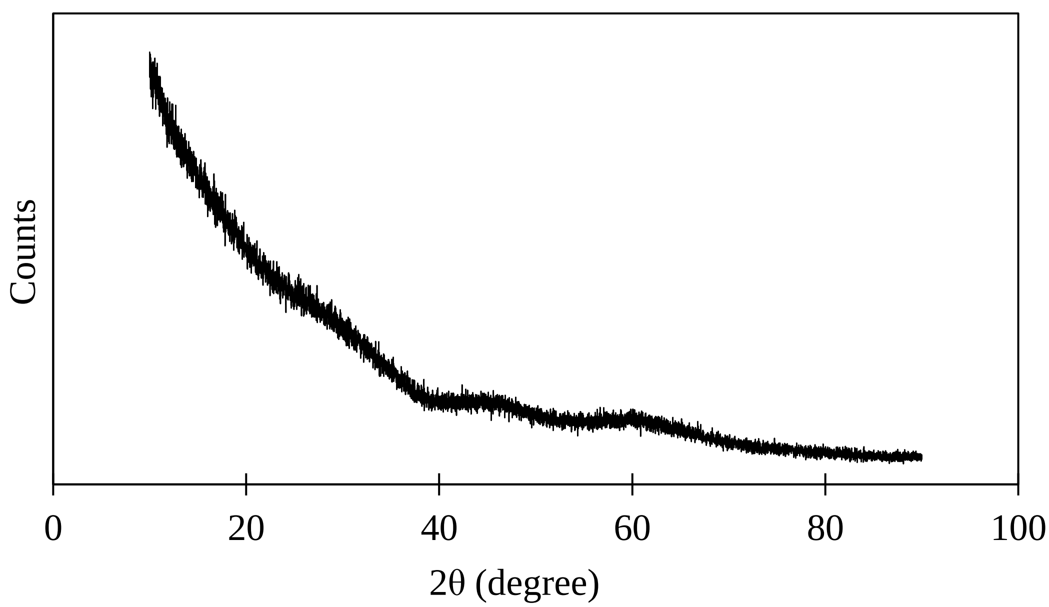

Fig. 6 XRD data for $TiO(OH)_2$

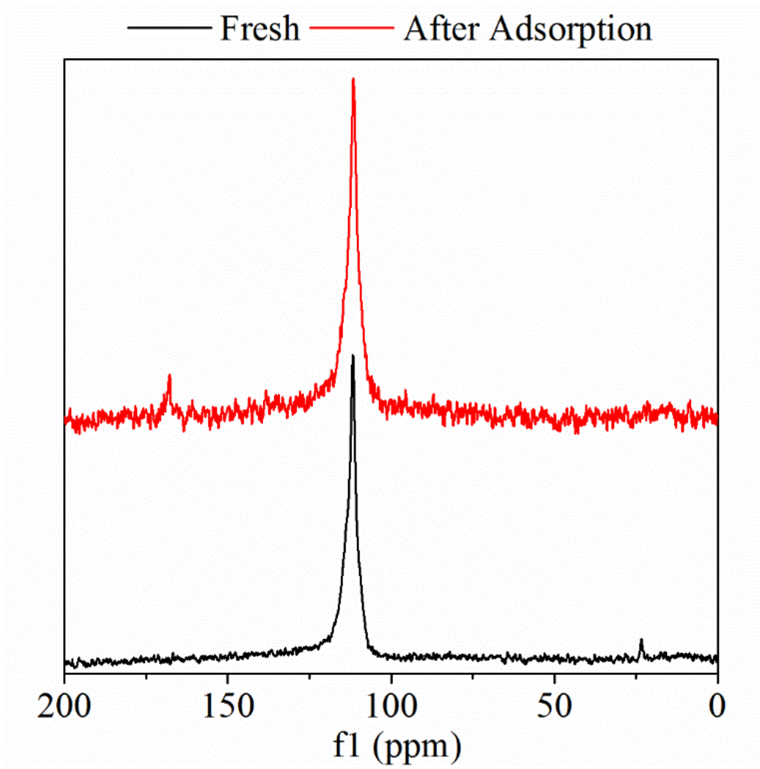

Fig. 7 C13 NMR of $TiO(OH)_2$ before and after the adsorption of carbonate

4.2 Adsorption Experiments

Variation of $TiO(OH)_2$ dosage in HCO_3^- adsorption

Experiments have been completed on variation of the $TiO(OH)_2$ dosage for bicarbonate removal. These results can be seen in Figure 8. The figure includes the linearly regressed pseudo second order kinetic model described previous overlaid the experimental data. The kinetic data derived from the linear regression can be seen in Table 2. The regression coefficients (r^2) were all above 0.9995, indicating the pseudo second order kinetic model chosen is an acceptable model. As anticipated, sorption of HCO_3^- increases with an increase in $TiO(OH)_2$ dosage. A final dosage of 4 g/L was chosen for all successive experiments.

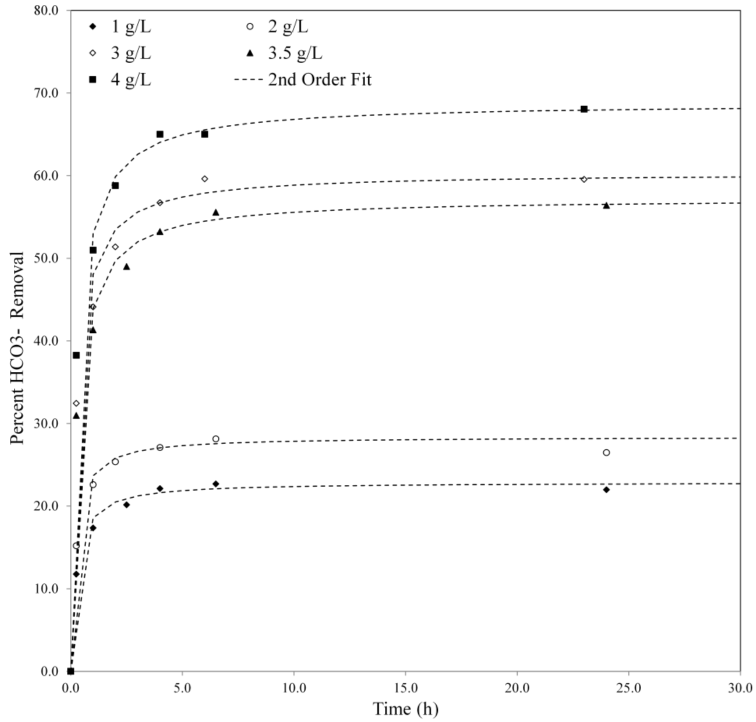

Fig. 8 HCO_3^- adsoprtion as a function of $TiO(OH)_2$ dosage. The pseudo-second order kinetic linear regression (dotted lines) are overlaid. Initial HCO_3 concetration was 4.8 mmol/L in a total volume of 1 L at a pH of 8.2.

Variation of Initial HCO_3^- Concentration

Initial bicarbonate concentrations are an important component in the science of their removal for both the kinetic and isotherm modeling. Therefore, experiments have been done in the variation of HCO_3^- initial concentrations. The data acquired can be seen in Figures 9-12. Figure 9 shows the lower concentrations common of alkaline waters. This data is also shown in Figure 10 as percent removal. All of initial concentrations in Figure 9 and 10 are within the slight to moderate hazard range of irrigation water (Table 2). The percentage removal in Figure 10 shows that many of the initial concentrations studied were brought down to no or slight irrigation hazard. The dotted lines of Figure 9 and 11 are the pseudo-second order kinetic applied. The values regressed from this kinetic analysis can be seen in Table 3. All the regression coefficients are over 0.999, signifying a suitable model. The kinetic constants decrease with an increasing initial concentration due to the slower kinetics adsorbing more bicarbonate. Figure 11 also show the TC analysis is very close to the autotirator analysis. This confirms the reliability, consistency, and accuracy of the titration analysis. Figure 12 shows the four isotherm models that were applied to the bicarbonate adsorption experiments. The R-P model resulted in the best fit, which indicates the adsorption mechanism is a mix of chemisorption and physisorption. The values regressed from these models are displayed in Table 4.

Table 2 Bicarboante/carbonate hazard of irrigation water

Bicarbonate (HCO_3) hazard of irrigation water (meq/L) [2]			
	None	Slight to Moderate	Severe
(meq/L)	<1.5	1.5-7.5	>7.5

Table 3 Kinetic data of varying initial HCO_3^- concentrations derived from the pseudo second order kinetic model

Variation of Initial HCO_3^- Concentration Kinetic Data			
Initial HCO_3^- (mmol/L)	k (g/(mg hr)	q_e (mg C /g)	r^2
1.4	1.2323	3.405	0.9999
2.7	0.4683	5.701	0.9999
3.9	0.3087	7.599	0.9998
5.0	0.3385	8.749	0.9993
6.1	0.2117	10.256	0.9996
12	0.2027	13.093	0.9995
24	0.1818	17.970	0.9998
48	0.0915	25.689	0.9990
72	0.0311	34.670	0.9991

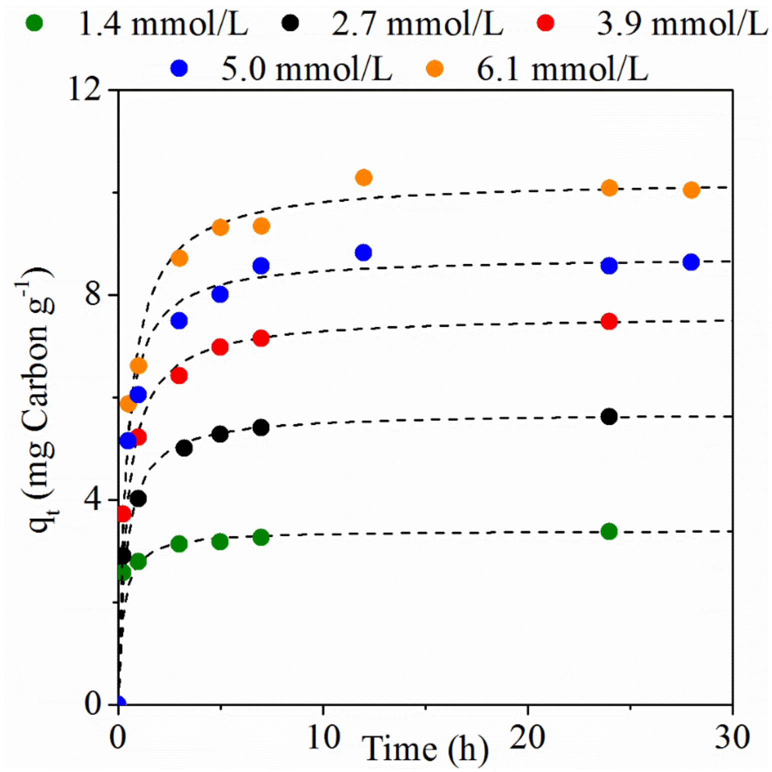

Fig. 9 **A**dsoprtion as a function of HCO_3^- initial concetration. Linearly regressed kinetic fit overlaid. Initial $TiO(OH)_2$ concetration was 4 g/L in a total volume of 1 L at a pH of 8.2.

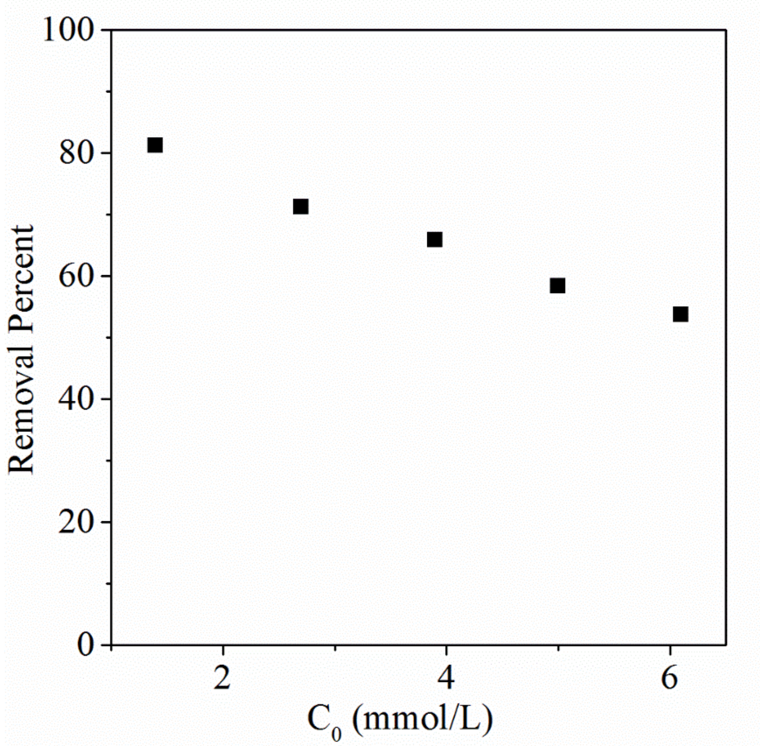

Fig. 10 Removal percentage of HCO_3^- as a function of HCO_3^- initial concetrations. Initial $TiO(OH)_2$ concetration was 4 g/L in a total volume of 1 L at a pH of 8.2.

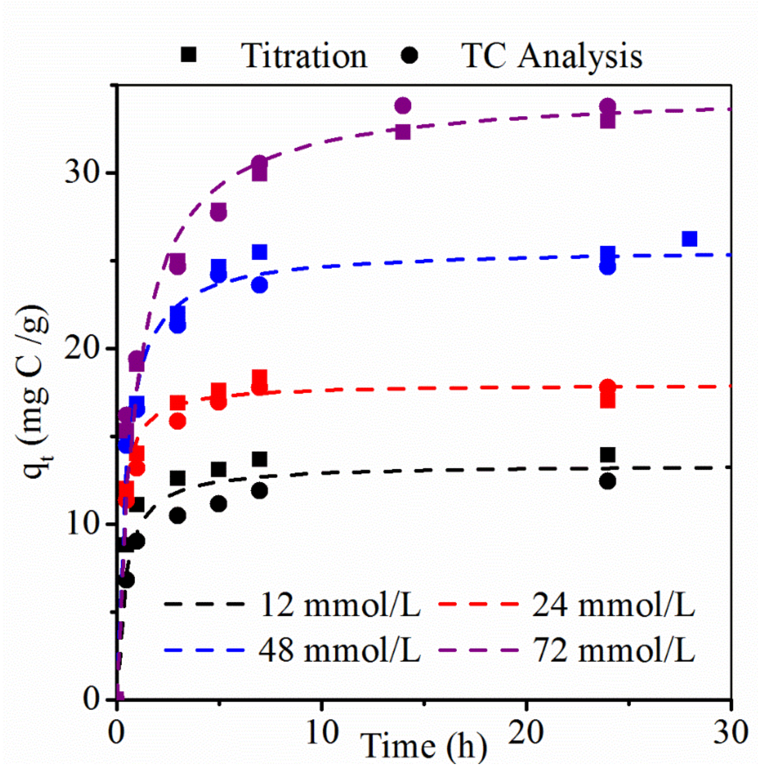

Fig. 11 HCO_3^- adsoprtion as a function of HCO_3^- initial concetration. Psuedo-second order kinetic fit overlaid. Initial $TiO(OH)_2$ concetration of 4 g/L in a total volume of 1 L at a pH of 8.2.

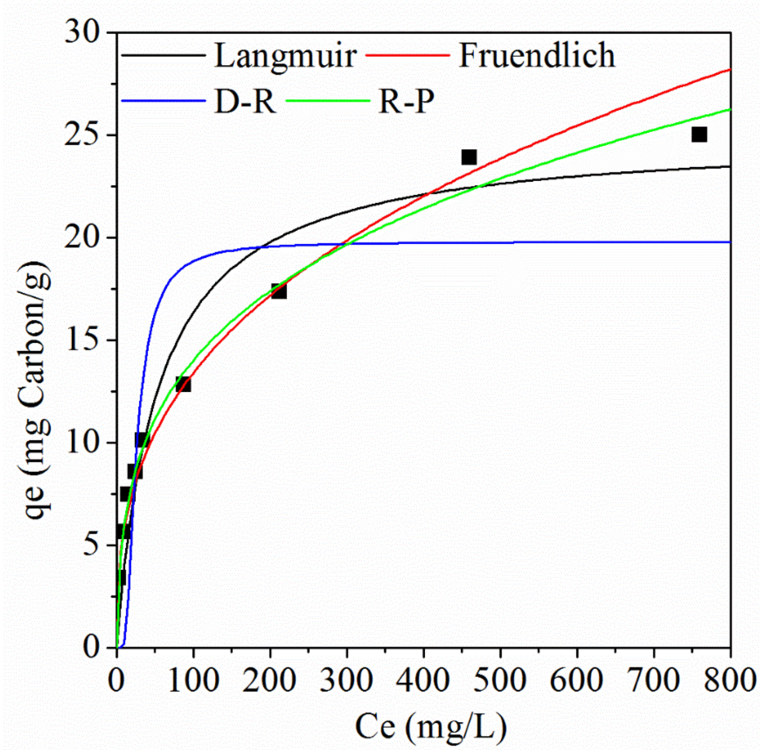

Fig. 12 HCO_3^- adsoprtion isotherms fits. Initial $TiO(OH)_2$ suspension was 4 g/L in a total volume of 1 L at a pH of 8.2.

Table 4 Isotherm parameters derived from non-linear regressions of adsorption data

Model	Parameters	
Langmuir	q_m (mg/g)	25.024
	b	0.019
	R^2	0.9358
Freundlich	K_f (mg/g)	2.577
	n	2.793
	R^2	0.9911
Dubinin-Rasushkevich	q_s (mg/g)	19.795
	k (kJ/mol)	83.715
	R^2	0.6080
Redlich-Peterson	K_r (L/g)	2.696
	a_r (mg $^{-1}$)	0.669
	g	0.718
	R^2	0.9990

CO_3^{2-} and HCO_3^{2-}/CO_3^{2-} Adsorption Experiments

Studies of carbonate (pH~11) and bicarbonate/carbonate (pH~10) removal are still in the preliminary phase, with more experiments currently being completed. Experimental data completed thus far can be seen in Figure 12. Experiments have shown that the introduction of $TiO(OH)_2$ into a carbonate system causes the equilibrium to shift and transforms the carbonate ion into bicarbonate. This is a promising find as previous experiments have shown the adsorption of bicarbonate onto $TiO(OH)_2$ is spontaneous therefore CO_3^{2-} removal can be achieved by first its transforming into HCO_3^- and then its adsorption onto $TiO(OH)_2$.

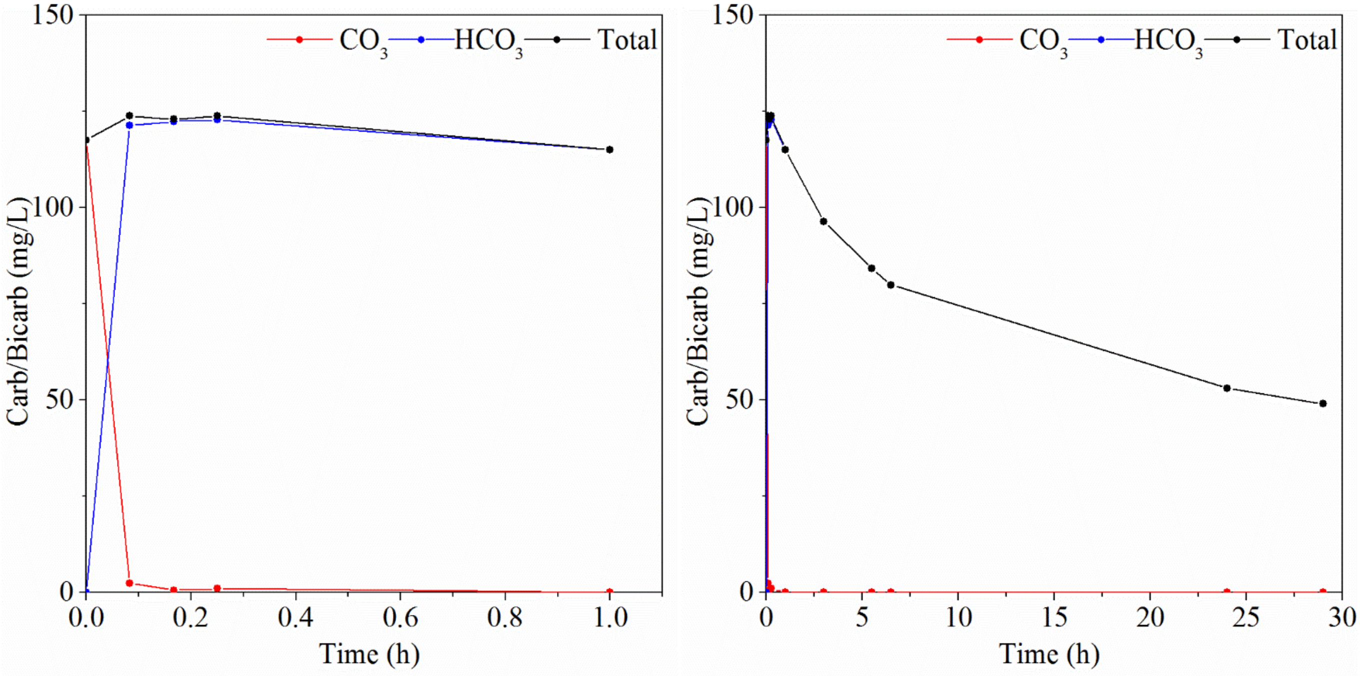

Fig. 13 CO_3^{2-} removal with an initial concetration of 125 mg/L. $TiO(OH)_2$ dose was 4 g/L in a total volume of 1 L.

5. Parties Involved, Publications, Presentations, etc.

5.1 Student Involvement and Citations

The completion of this project has been assumed by the following:

Andrew Thomas Jacobson is a PhD candidate in chemical engineering at the University of Wyoming. Andrew was the leading researcher of the project and was tasked with experimental design, experimental execution, sample analysis, and data analysis.

Maryam Irani is a PhD candidate in chemical engineering with a final examination date of May, 10 2018. Maryam was the assistant researcher to the project and helped with performing experiments.

Mohammad Ali Assiri earned his PhD in 2016 in chemistry at the University of Wyoming. He helped with the sorbent characterization experiments.

5.2 Involved Student Publications during Project Period

The following research has been published by the students involved during the project time period:

- Andrew T. Jacobson and Maohong Fan, *Evaluation of natural goethite on the removal of arsenate and selenite from water Journal of Environmental Sciences,* In Press, Available online 30 April 2018
- Maryam Irani, Andrew T. Jacobson, Khaled A.M. Gasem, Maohong Fan, *Modified carbon nanotubes/tetraethylenepentamine for CO_2 capture*, Fuel 206 (2017) 10–18.
- Maryam Irani, Khaled A.M. Gasem, Bryce Dutcher, Maohong Fan, *CO_2 capture using nanoporous $TiO(OH)_2$/tetraethylenepentamine*, Fuel 183 (2016) 601–608.

5.3 Presentations

- Andrew T. Jacobson (2017, August) *A New Multifunctional Sorbent for the Treatment of Coproduced Waters (CWs) from the Energy Industry.* Presented at Wyoming Water Development Commission Office, Cheyenne, WY.
- Andrew T. Jacobson (2018, May) *Evaluation and Development of Solid Adsorbents for Water Remediation.* Presented at PhD Preliminary Examination, Laramie, WY.

5.4 Notable Awards and Achievements

- Andrew T. Jacobson was a NSF EE Nanotechnology Fellow at UW.
- Mohammad Ali Assiri received his PhD in chemistry during the project period.
- Maryam Irani received her MS in chemical engineering during the project period.

6. References

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11. Foo, K.Y. & Hameed, B.H. (2010) Insights into the modeling of adsorption isotherm systems. Chem. Eng. J., 156, 2-10.

Produced Water Treatment with Smart Materials for Reuse in Energy Exploration

Basic Information

Title:	Produced Water Treatment with Smart Materials for Reuse in Energy Exploration
Project Number:	2017WY93B
Start Date:	3/1/2017
End Date:	2/28/2019
Funding Source:	104B
Congressional District:	1
Research Category:	Water Quality
Focus Categories:	Treatment, Water Quality, Water Use
Descriptors:	None
Principal Investigators:	Dongmei Li

Publications

There are no publications.

USGS-WWDC Water Research Program Annual Progress Report

Project Title: **Produced Water Treatment with Smart Materials for Reuse in Energy Exploration**

Prepared by Dongmei "Katie" Li
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Phone: (307) 766-3592

Annual Report

Abstract

Hydraulic fracturing, also referred to as Hydrofracturing, has enabled the economical recovery of gas and oil from the unconventional reservoirs, such as Marcellus Shale and Niobrara. Produced water refers to the water that returns to the surface, typically 10 to 30% of the original injected amount. The produced water is composed of the original components in the fracturing fluid as well as any materials that may have entered it through its contact with the surrounding geology and groundwater, which generally results in an aqueous mixture rich in organic and inorganic substances. Produced water management has been discussed and reported by government agencies and industrial partners. The soluble organics often result in problematic re-injection of the produced water (for pressure control), such as unpredictable pore plugging of the fractures, when used to make up part of the hydraulic fracturing fluid. However, to remove the dissolved organic compounds (DOC) requires advanced water treatment that can be as costly as $8/barrel in Wyoming. One of the primary reasons for high costs results from fouling on commercial surface treatment facilities caused by DOC. The fouling issue is a concern because it results in decreased process efficiency and, consequently, increased operating and capital costs. Here we propose to develop hybrid membranes by depositing smart materials, such as TiO_2 nanoparticles, onto commercial membranes (the central pieces of a commercial water/oil separation module) via a recently developed technique in the Li lab. Thanks to the photo-oxidative and hydrophilic properties of smart materials, the hybrid membrane allows decomposition of DOC, consequently breaking up aggregations of organic molecules before the formation of much larger particles. As such, the proposed technology prevents pore plugging when rejecting produced water as part of the hydraulic fracturing fluid, providing a cost-effective reuse in energy exploration loop and, alleviating environmental concerns of the citizens of Wyoming.

Problem Statement

***Statement of critical regional or State water problem*:** Due to the vast amount of water used in hydrofracturing process, the cost of produced water treatment and the availability of water resources have become barriers for hydrofracturing in Wyoming. The proposed research addresses these challenges by developing hybrid membranes that can self-clean their surfaces, in addition to increase clean water flux, which provides a cost-effective, energy-efficient produced water treatment approach for reuse.

Statement of results or benefits: We anticipate that this project will generate the following outcomes: 1) Novel hybrid membranes that can decompose dissolved organics in produced water, consequently reducing water treatment costs in capital and operation and enabling hydrofracturing practice in acrid areas in Wyoming. 2) Generation of testing data related to water recovery for different produced water chemistries. Due to the complex nature of produced water chemistry, addressing the dissolved organics in produced has been challenging on a well-to-well base. Since the proposed TiO_2 nanoparticles can decompose the organics by the radicals generated by photon, the hybrid membranes can self-clean without the need to 'identify' those compounds. 3) Through PI's existing partnership with service and exploration companies, water sample from the drilling field will be tested, increasing our understanding on whether and how the treated produced water can be reused for irrigation and hydrofracturing.

Objectives of the project and a timetable of activities: We are proposing the construction of hybrid membranes consisting of a continuous polymer phase that contains pore structures that will be modified by TiO_2 nanoparticles with well-controlled size and distribution density via both wet-chemistry and Plasma Enhanced Atomic Layer Deposition (PEALD). The unique functionalities of TiO_2 nanoparticles have been well recognized, studied and applied to tailor membrane structures to mitigate fouling and enhance flux. Although there is no limitation on the starting membrane materials, we will primarily focus on use of microfiltration (MF) and reverse osmosis (RO) polymeric membrane supports since they span the range of pore sizes used in produced water treatment systems, where oftentimes MF was used as a pretreatment step for RO desalination in produced water treatment. We will modify commercial flat membrane samples and test them in bench scale module in the PI's lab. Briefly, to fabricate a hybrid membrane material, TiO_2, as small as 1-2 nm, will be deposited onto a polymer membrane substrate via solution and vapor deposition approaches. While traditional in-situ nanoparticles deposition has been problematic due to nanoparticle aggregation, the proposed approach will take advantage of cutting-edge surface chemistry by adding a short, semi-rigid polymer chain so that the nanoparticles can be deposited on the substrate surface 'indirectly', with a bonding agent guiding the deposition to minimize nanoparticle aggregation and a strengthened bonding between the nanoparticle and modified substrate surface as shown in Fig. 1.

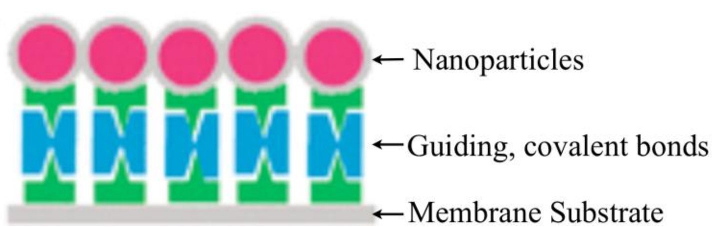


Figure 1. *Guided Nanoparticle Deposition with Strengthened Bonding Between Membrane Substrate and Nanoparticles*

For comparison, Plasma enhanced atomic layer deposition (PEALD) will be employed since vapor phase deposition historically provides more accurate control in deposition density and particle size.

Before the PEALD deposition, the membrane surface will go through plasma treatment to enhance adhesion between TiO_2 nanoparticles and membrane surface. The nanoscale deposited particle size is achieved by the nature of atomic layer deposition (ALD), which consists of two half reactions in vapor phase, resulting in its self-limiting nature [Figure 2]. By simply controlling the number of ALD cycles, the size of deposited TiO_2 nanoparticles can be accurately controlled. In addition, the density of hydroxyl groups on the membrane surface before ALD deposition is proportional to the density of the deposited TiO_2, which can be adjusted by tuning both the number of ALD cycles and surface plasma treatment process parameter.

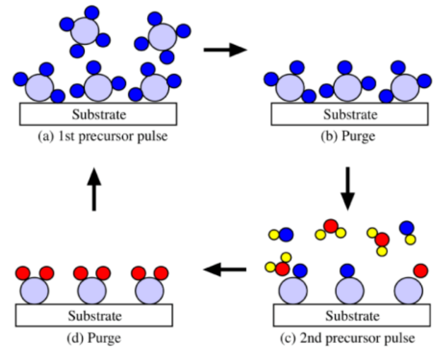


Figure 2. *Schematic of ALD*

Proposed Project Objectives

In situ photo-oxidative, hydrophilic TiO_2 nanoparticles deposited via easily scalable ALD process may have the potential to heavily impact the field of cost-effective, sustainable produced water treatment by enhancing water flux and minimizing fouling caused by organic matters. To investigate the potential of this novel hybrid membrane manufacturing process, we will focus on three research goals: Research Goal #1 establishes TiO_2 ALD deposition conditions using common polymer materials that have shown promise in the past or are currently being used by researchers for RO or MF applications. Research Goal #2 will explore bench scale testing of the hybrid membranes in terms of fouling resistance and permeate flux using synthetic hydrofracturing produced water sample. Naturally, we are interested in identifying the optimal deposition conditions that generates lowest fouling with enhancing permeability for long-term use, but also evaluating the short-term performance of the hybrid material will shed light on importance of how to further optimize process parameters. In addition, we will begin to evaluate the long-term membrane performance. Research Goal #3 will investigate how irradiation intensity and duration affect hybrid membrane performance in decomposing dissolved organic in produced water.

Research Goal #1: *To deposit TiO_2 via ALD onto common RO/MF Polymeric Membranes.*

Research Goal #2: *To explore bench testing of the hybrid membranes in terms of fouling resistance and permeate flux using synthetic hydraulic fracturing produced water sample.*

Research Goal #3: To study the effect of irradiation

Progress to Date

Technical progress and Publications

During the past year of this grant, we continued to work on all three research goals discussed above. Specifically, detailed surface and cross-sectional characterization using x-ray photoelectron spectroscopy (XPS) and high resolution transmission electron spectroscopy (HRTEM), was carried out on polyvinylidene fluoride (PVDF) ultrafiltration membranes that were pretreated by dopamine (PDA) followed by depositing TiO_2 via ALD. Part of the surface characterization results was incorporated into our manuscript that was recently resubmitted to American Chemistry Society (ACS) Omega, titled '*Elucidation of Titanium Dioxide Nucleation and Growth on Polydopamine Modified Nanoporous PVDF Substrate via Low Temperature Atomic Layer*'. The HRTEM and filtration data will be disseminated in two additional manuscripts that are in preparation. Our technical contribution include: 1) As shown in **Fig. 3** below, surface properties, such as contact angles, are not linearly related to the number of ALD cycles in the range of TiO_2 nucleation and growth phase (<100). As a result, we find that membrane surfaces can be more finely controlled than what was reported in open literature, which consequently affect the optimum balance between water flux and fouling resistance. This finding can also be very useful in wearable sensors and smart textile fields. 2) **Fig. 4** shows that membrane pores are not significantly blocked by TiO_2 nanoparticles, which we originally hypothesized.

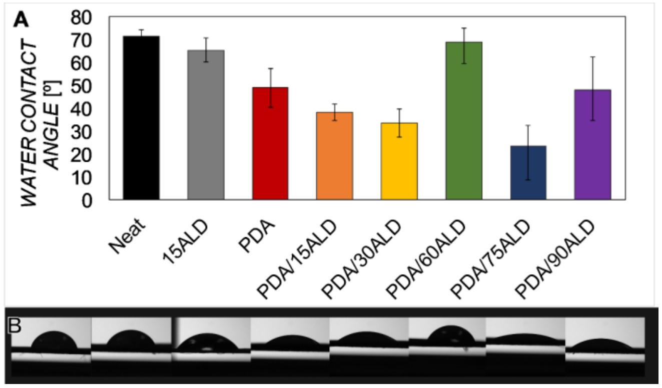


Figure 3. (a) Water contact angles for neat, 15ALD, PDA, and PDA followed by 15/30/60/75/90 ALD cycles samples and (b) corresponding water droplet images (same sample order from left to right as panel a).

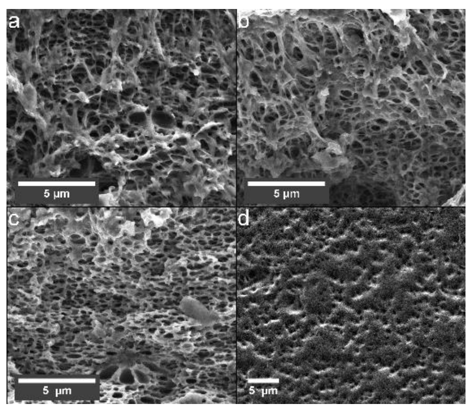


Figure 4. Cross-sectional SEM images of (a) neat PVDF, (b) PDA, and (c) PDA/90ALD, and (d) the top surface of PDA/90ALD.

Built upon the progress and learning from the past two years, we recently embarked on the following: 1) using a layer-by-layer approach (LBL) to deposit anatase TiO_2 particles onto UF membranes, and, 2) investigate the effect of irradiation on water flux and decomposition of naphthenic acid of the hybrid membranes fabricated via the LBL technique.

<u>Students who have been supported partially or fully and their achievements</u>

The WWDC funding has partially or fully supported Audra DeStefano (M.S. candidate), Jiashi Yin (Ph.D. candidate), Shuai Tan (Ph.D.) and Anqi Qu (Ph.D.). These highly motivated students have won national awards, passed their Ph.D. and M.S. defense and preliminary exams, as follows:

<u>Ian Hammontree and James "Max" Weiss</u> <u>(UW undergraduates, senior):</u> Both Ian and Max joined the Li group in Summer 2017 as undergraduate researchers, working on various aspects of the project water project. Their experience in the Li lab sparked strong interests in pursuing graduate degress. Ian will continue his research endeavor in the Li group as a M.S. student starting summer 2018, while Max will be a graduate student at Colorado School of Mines.

<u>Audra DeStefano (M.S.):</u>

1) Audra won the super competitive Elia Klein Travel award that is given to graduate students worldwide in 2016, which partially funded her trip to present a poster at North American Membrane Society (NAMS) annual meeting held in Bellevue, WA (May, 2016).
2) Audra was nominated as Own It! outstanding female undergraduate in Spring 2016.
3) Audra was awarded 2016-17 Mountain West Scholar-Athlete of the Year for her exceptional athletic, academic accomplishments and community services.
4) Audra's gave an outstanding oral at 2017 International Congress on Membranes and Membrane Processes (ICOM). This conference is held every three years and known to be extremely selective for oral presentations and has over 30% rejection rate.
5) Audra successfully defended her M.S. thesis and is accepted into multiple prestigious Chemical Engineering Ph.D. programs in the country, including Cornell University, University of Minnesota, University of California at Santa Barbara. She chose to go to UC Santa Barbara to prepare herself to be a faculty member.

<u>Jiashi Yin (Ph.D.)</u>

1) Jiashi won the super competitive Elia Klein Travel award that is given to graduate students worldwide in Spring 2017, which will partially fund her trip to present a poster at ICOM 2017 in San Francisco, CA (July, 2016).
2) Jiashi successfully passed her preliminary exam in Spring 2017.
3) Jiashi is preparing a manuscript on fabricating hybrid graphitic membranes for liquid separation including produced water treatment.

<u>Shuai Tan (Ph.D.)</u>

1) Shuai successfully defended his Ph.D. in August 2016.
2) Shuai has published 4 peer-reviewed journal papers at high quality journals and two issued US patents, with an additional manuscript submitted in Spring 2017.
3) Shuai presented his work on catalytic nanoparticles at Rocky Mountain Catalysis Society in March 2016, at Provo, Utah.
4) Shuai has been a postdoc researcher in my group working on fabricating supercapacitors using carbon fibers derived from Wyoming coal.

<u>Anqi Qu (Ph.D.)</u>

1) Anqi Qu reached out to me from Columbia University (New York, US), while finishing her M.S. at Columbia University. She has learned a ton about the project and just did a great group meeting presentation about her literature survey.

<u>Conference presentations</u>

The WWDC funding has enabled us to travel to national conferences for students to present our work (see above section for detail) and the PI to chair or co-chair sessions including:
North American Membrane Society (NAMS) (May, 2016)
American Institute of Chemical Engineers (AIChE) (November, 2016)
Material Science and Engineering Symposium poster session (April, 2017)
International Congress on Membranes and Membrane Processes (ICOM) (July-August, 2017)
American Chemistry Society (ACS) (March, 2018)
Material Science and Engineering Symposium poster session (March, 2018)

Information Transfer Program Introduction

Information transfer activities for Wyoming are reported under Project 2015WY90B: Wyoming Information Transfer, Greg Kerr, Director, UW Office of Water Programs. The FY17 Annual Report for the project is given below.

Wyoming Information Transfer

Basic Information

Title:	Wyoming Information Transfer
Project Number:	2015WY90B
Start Date:	3/1/2017
End Date:	2/28/2020
Funding Source:	104B
Congressional District:	1
Research Category:	Not Applicable
Focus Categories:	None, None, None
Descriptors:	None
Principal Investigators:	Greg Kerr

Publication

1. Wilkinson, C., J.A. Robison, L.J. MacDonnell, J.E. Thorson, B.W. Griggs, M. Bryan, and A. Mackinnon, 2015. Big Horn General Stream Adjudication Symposium Division, Wyoming Law Review, Vol. 15, No. 2, University of Wyoming, College of Law, 591 pgs. (Symposium co-sponsored by University of Wyoming Office of Water Programs.)

Wyoming Information Transfer

FY17 Annual Report

Greg Kerr, Director, University of Wyoming Office of Water Programs, email: rrek@uwyo.edu

Introduction

Information transfer activities are an important component of the Wyoming Water Research Program (WRP). Activities include Office of Water Program (OWP) interactions with the Wyoming Water Association, Wyoming Water Forum, Wyoming Water Development Commission, Wyoming Legislative Select Water Committee, Wyoming Weather Modification Pilot Program Technical Advisory Team, and other water-related interests such as the Wyoming Stock Growers, Wyoming Governor's Water Strategy Group, Wyoming State Legislature House and Senate Agriculture Committees, University of Wyoming Water Interest Group, and Wyoming Center for Environmental Hydrology and Geophysics Water Interest Group. The WRP supports other technology and information transfer activities throughout the year. In order to facilitate dissemination of results of WRP funded research projects, and other closely related water research projects, information transfer includes support of peer publications and conference and meeting presentations for PIs and students of ongoing and completed WRP funded research projects and other closely related projects. The OWP maintains a web site which includes the most recent request for proposals and project reports. The WRP Advisory Committee serves as a group which facilities information transfer throughout various State and Federal agencies.

The OWP Director, Greg Kerr, has averaged over thirty information dissemination related presentations, meetings, and service activities each of the past few years. The following includes descriptions of the major interactions within the information transfer activities and general descriptions of the other interactions and of the as-requested information transfer activities which involve University personnel including both faculty and students.

WRP Advisory Committee

The WRP Advisory Committee serves as a group which facilities information transfer through various State and Federal agencies. The Advisory Committee consists of representatives from nine State, Federal, and Public agencies. The OWP Director meets at a minimum twice during the year with the WRP Advisory Committee. The project PIs report to the Institute Advisory Committee on an annual basis. Presentations discussing final results are made by PIs of projects which were completed during the year at the July advisory committee meeting. Presentations discussing interim results are made by PIs of continuing projects at the fall/winter or spring advisory committee meetings.

- UW Water Research Program. WRP Advisory Committee meeting to develop FY2018 RFP topics and research priorities. Cheyenne, WY., April 27, 2017.
- Wyoming Water Research Program Meeting. WRP Advisory Committee review and ranking of water research projects. Cheyenne, WY., December 8, 2017.

Wyoming Water Development Commission (WWDC)

The Wyoming Water Development program provides, through a commission, procedures and policies for the planning, selection, financing, construction, acquisition, and operation of water projects. This includes projects for the conservation, storage, distribution and use of water. The commission is composed of 10 members appointed by the governor to represent the four state water divisions and the Wind River Reservation. The Wyoming Water Development Office (WWDO), which administers the program, is staffed by 26 professional, legal, and support employees. The Program receives funding from severance tax distributions. The OWP Director attends all meetings and workshops of the WWDC and reports on a regular basis on activities of the WRP (a list of FY17 meetings is given below). The Wyoming Water Development Program provides funding each year to the UW Office of Water Programs to fund non-project water related research. The OWP Director serves as the University of Wyoming Advisor to the WWDC (the other three advisors include the Wyoming State Engineer and representatives from the State Attorney General's Office and the Wyoming Business Council).

- Wyoming Water Development Commission workshop and project approval meetings. Cheyenne, WY., March 2-3, 2017.
- Wyoming Water Development Commission/Select Water Committee joint workshop. Presentation on the UW Office of Water Programs and Water Research Program. Cheyenne, WY., June 8-9, 2017.
- Wyoming Water Development Commission/Select Water Committee joint meeting/summer tour. Green River, WY., August 23-25, 2017.
- Wyoming Water Development Commission/Select Water Committee joint workshop. Presentation on the UW Office of Water Programs and Water Research Program- preliminary funding recommendation. Casper, WY., November 1-2, 2017.

Wyoming Legislative Select Water Committee

The Select Water Committee provides legislative oversight for the Wyoming Water Development Program and reviews and approves funding recommendations developed by the WWDC. The committee's approval comes in the form of its willingness to sponsor the "Omnibus" Planning and Construction bills. The Select Water Committee is comprised of 6 senators and 6 representatives. The Select Water Committee meets both jointly with the WWDC and separate from the WWDC. The OWP Director attends all meetings of the Select Water Committee and reports on a regular basis on activities of the WRP.

- Wyoming Water Development Commission workshop and project approval meetings. Cheyenne, WY., March 2-3, 2017.
- Wyoming Water Development Commission/Select Water Committee joint workshop. Presentation on the UW Office of Water Programs and Water Research Program. Cheyenne, WY., June 8-9, 2017.
- Wyoming Water Development Commission/Select Water Committee joint meeting/summer tour. Green River, WY., August 23-25, 2017.
- Wyoming Water Development Commission/Select Water Committee joint workshop. Presentation on the UW Office of Water Programs and Water Research Program- preliminary funding recommendation. Casper, WY., November 1-2, 2017.

- Legislative Select Water Committee meeting. Final approval of Omnibus Water Bill funding. Water Research Program FY2018 projects. Cheyenne, WY., April 3, 2018.

Wyoming Weather Modification Pilot Program Technical Advisory Team

Funded by the Wyoming Water Development Commission, the Wyoming Weather Modification Pilot Program (WWMPP) has been conducted to assess the feasibility of increasing Wyoming water supplies through winter orographic cloud seeding. The program has been ongoing since 2005. The WWMPP consisted of an orographic cloud seeding research program in three Wyoming mountain ranges: the Medicine Bow, Sierra Madre, and Wind River Ranges. A Technical Advisory Team (TAT) was established early during the project to provide guidance to the Wyoming Water Development Office on the oversight of the program. The TAT consists of representatives from the many participants in the WWMPP and other interested stakeholders. The OWP Director is included among the representatives on the TAT (FY17 Director activities are listed below). In addition, the WRP has funded several ancillary glaciogenic cloud seeding research projects complementary to the WWMPP.

- North American Weather Modification Council, Wyoming Weather Modification new projects update. Boise, ID., April 16, 2017.
- Weather Modification Association -- Annual Conference, Wyoming Weather Modification program update. Boise, ID., April 16-19, 2017.
- WY Weather Modification Technical Advisory Team - Summer 2017 Meeting, University of Wyoming, Laramie, WY., July 12, 2017.

Wyoming Water Forum

The Wyoming Water Forum is an information exchange mechanism in an informal setting that occurs from September to May each year. The Water Forum provides state and federal agency personnel a regular opportunity to share information and insight on water activities that are ongoing in their respective agencies. At each monthly meeting, a special program is presented providing a more in-depth review of a particular water related issue or topic. Example topics of discussion at past Water Forum meetings range from agriculture and water quality, instream flow, watershed case studies, groundwater, invasive species management and water supply updates. The State Engineer serves as the Chairman of the Wyoming Water Forum. The OWP Director attends the Water Forum meetings on a regular basis (a FY17 list is given below), participates in the discussions, and presents summaries on WRP activities.

- Wyoming Water Forum, Presentation on Water Research Program update. Cheyenne, WY., March 14, 2017.
- Wyoming Water Forum, Presentation on Water Research Program update. Cheyenne, WY., April 11, 2017.
- Wyoming Water Forum, Presentation on Water Research Program update. Cheyenne, WY., May 9, 2017.
- Wyoming Water Forum, Water Research Program final project reports. Cheyenne, WY., September 12, 2017.
- Wyoming Water Forum, Presentation on Water Research Program update. Cheyenne, WY., October 10, 2017.
- Wyoming Water Forum, Presentation on Water Research Program update. Cheyenne, WY., November 14, 2017.

- Wyoming Water Forum, Presentation on Water Research Program update. Cheyenne, WY., January 9, 2018.
- Wyoming Water Forum, Presentation on Water Research Program update. Cheyenne, WY., February 13, 2018.

Wyoming Water Association

The Wyoming Water Association (WWA) is the only statewide water resources association serving as a voice representing all Wyoming water interests. Membership consists of any individual, organization, agency, or group wishing to participate, including: private citizens, elected officials, and representatives of business, government agencies, industry, and water user groups and districts. Association activities include efforts to educate the public, government agency personnel, and elected decision makers through the association's quarterly Wyoming Water Flow newsletter, the annual meeting and educational seminar, a summer meeting and tour, and a winter meeting and legislative review sessions. The OWP Director's participation in the WWA includes service as a Board Advisor, co-sponsor of the Annual Meeting, and inclusion in the Summer Water Tour. PIs and students of WRP supported projects present at the Annual Meeting. FY17 OWP Director WWA activities and an agenda for the 2017 WWA Annual Meeting are given below.

- Wyoming Water Association Board meeting, (Advisor), Lander, WY., June 19, 2017.
- Wyoming Water Association Summer Water Tour, (Advisor), Lander, WY., June 20, 2017.
- Wyoming Water Association Board meeting (Advisor), Sheridan, WY., October 24, 2017.
- Co-Sponsor Wyoming Water Association Annual Meeting & Educational Seminar, University of Wyoming Water Research Initiatives. Sheridan, WY., October 25-27, 2017.
- Wyoming Water Association Board Meeting, Legislative Review, (Advisor), Cheyenne, WY., February 14, 2018.
- Wyoming Water Association Board Meeting, Legislative Review, (Advisor), Cheyenne, WY., February 21, 2018.
- Wyoming Water Association Board Meeting, Legislative Review, (Advisor), Cheyenne, WY., February 28, 2018.

Wyoming Water Association 2017 Annual Meeting & Educational Seminar

Navigating a Sea of Change

UPPER MISSOURI WATER ASSOCIATION

Wyoming Water Association,
UW Office of Water Programs,
& Upper Missouri Water Association

Joint Annual Meeting & Educational Seminar

Holiday Inn—Sheridan, Wyoming
October 24-27, 2017

Wyoming Water Association 2017 Annual Meeting & Educational Seminar

WYOMING WATER ASSOCIATION,
UW OFFICE OF WATER PROGRAMS,
& UPPER MISSOURI WATER ASSOCIATION

JOINT ANNUAL MEETING
& EDUCATIONAL SEMINAR

HOLIDAY INN—SHERIDAN, WYOMING
October 24-27, 2017

"Navigating a Sea of Change"

TUESDAY, October 24 (Pre-Session)

1:00 p.m.	WWA Board of Directors' Facilitated Work Session (Chaparral Room)
6:00 p.m.	WWA Board of Directors' Dinner Meeting (Chaparral Room)

WEDNESDAY, October 25 (Annual Meeting)

7:00 a.m.	Upper Missouri Water Association Breakfast Board Meeting (Solitude Room)
8:00 a.m.	CONVENTION REGISTRATION BEGINS (Foyer)
8:00 a.m.	VENDOR BOOTH SET UP

WEDNESDAY, October 25 (Annual Meeting)

MORNING PROGRAM SESSION (Sibley/Diamond Rooms)
MODERATOR: Sue Lowry, Board Member Wyoming Water Association, Cheyenne, WY

9:00 a.m.	Call to Order of Joint Annual Meeting and Opening Remarks **Frank Grimes**, President, Wyoming Water Association, Pinedale, WY **Norman Haak,** President, Upper Missouri Water Association, Oakes, ND **Greg Kerr**, Director, University of Wyoming, Office of Water Programs, Water Research Program
9:15 a.m.	**Roger Miller,** Mayor, Sheridan, "Welcome to Sheridan"
9:20 a.m.	**BUREAU OF RECLAMATION AREA MANAGERS** **Arden Freitag**, Dakotas Area Office **Steve Davies**, Montana Area Office **Carlie Ronca**, Wyoming Area Office
10:15 a.m.	**Annick Miller Rivera**, Water Strategies, LLC, "Inside Washington Update"
11:00 a.m.	MORNING BREAK (Foyer)
11:15 a.m.	**STATE ENGINEER PANEL** **John Paczkowski**, Assistant State Engineer, North Dakota **Mark Elison**, Regional Manager, Billings, Water Resources Division, Montana **Pat Tyrrell**, State Engineer, Wyoming

NOON LUNCHEON (Geneva/Solitude Rooms)

12:15 p.m.	LUNCH

WEDNESDAY AFTERNOON PROGRAM BREAKOUT SESSIONS

IRRIGATION/CONSERVATION WORKSHOP (Sibley)
MODERATOR: Frank Grimes, President, Wyoming Water Association, Pinedale, WY

1:30 p.m. **Travis Conklin**, Engineering Associates, "War on the Wilwood: Achieving a Balance between the Environment and Agriculture"

2:15 p.m. **Lynn Cornia**, Natural Resources Conservation Service, "Technical and Financial Assistance Available to Districts from the NRCS"

3:00 p.m. AFTERNOON BREAK (Foyer)

3:15 p.m. **Mahonri Williams**, Bureau of Reclamation – Wyoming Area Office, "Funding Opportunities for Irrigation Districts from the Bureau of Reclamation"

4:00 p.m. **Jay Schug**, Project Manager, Anderson Consulting Engineers, Inc., Fort Collins, CO, "Technology-Driven Irrigation Planning Tools"

5:00 p.m. ADJOURN

MUNICIPAL/ENVIRONMENTAL WORKSHOP (Diamond)
MODERATOR: Brent Lathrop, Board member, Wyoming Water Association, Cheyenne, WY

1:30 p.m. **Dena Egenhoff**, Board of Public Utilities, City of Cheyenne, "Water Supply Sustainability"

2:15 p.m. **Greg Gable**, DOWL, Sheridan, "Shiloh Conservation Area for Stormwater Control, Billings, MT"

3:00 p.m. AFTERNOON BREAK (Foyer)

3:15 p.m. **Lorraine Werner**, Program Director, USDA Community Facilities, Water and Environmental Programs, Casper, WY, "Funding Partnerships and Options from USDA Rural Development"

4:15 p.m. **Lane Thompson**, City of Sheridan, "City of Sheridan and the use of Gutter Bins"

5:00 p.m. ADJOURN

WEDNESDAY EVENING PROGRAM SESSION

6:00 p.m. SOCIAL TIME AND SILENT AUCTION
(Geneva/Solitude Rooms)

7:00 p.m. BANQUET, SPEAKER, AND PRESENTATIONS

PRESENTATION: WWA Scholarship Recipient Recognition and Essay Presentations, Ryan Erickson, WWA Scholarship Chair, Afton, WY

PRESENTATION: UMWA Distinguished Service Awards, Mick Jennings, Vice President, Upper Missouri Water Association, Oral, SD

SPECIAL ADDRESS: **Dr. Richard A. Marston,** University Distinguished Professor Emeritus, Kansas State University, Manhattan, KS, "When Water Moves Across and Along Boundaries"

THURSDAY, October 26 (Annual Meeting Continues)

7:00 a.m. CONTINENTAL BREAKFAST

8:00 a.m. Wyoming Water Association Annual Business Meeting
(Sibley/Diamond Rooms)
PRESIDING: **Frank Grimes**, President, Wyoming Water Association, Pinedale, WY

MORNING PROGRAM SESSION (Sibley/Diamond Rooms)
MODERATOR: Dayton Alsaker, Board Member Wyoming Water Association, Sheridan, WY

9:00 a.m. **Harry LaBonde, Jr.**, Director, Wyoming Water Development Office, Cheyenne, WY, "Extension of the Platte River Recovery Implementation Program (PRRIP)"

9:45 a.m. **Sarah Tessendorf**, Project Scientist, National Center for Atmospheric Research, Boulder, CO, "Investigating the Feasibility of Cloud Seeding in the Bighorn Mountains"

10:15 a.m. MORNING BREAK

THURSDAY, October 26 (Continued)

10:30 a.m. **ADVISOR UPDATE**

Pat Tyrrell, Wyoming State Engineer, Wyoming State Engineer's Office
Harry LaBonde, Jr., Director, Wyoming Water Development Office
Brian Lovett, Water Quality Division Administrator, Wyoming DEQ
TBD, Wyoming Game & Fish Department

JOINT ANNUAL MEETING & EDUCATIONAL SEMINAR LUNCHEON
(Geneva/Solitude Rooms)

12:00 p.m. LUNCH

The WWA Water Resources Educational Seminar (for CEU and CLE credits) will be conducted beginning Thursday afternoon, October 26th, with the noon luncheon and continuing through adjournment at 12:00 noon on Friday, October 27th. Attendees of the Joint WWA/ UMWA Annual Meeting and/or WWA Educational Seminar are all invited to the joint luncheon on Thursday.

WYOMING WATER ASSOCIATION EDUCATIONAL SEMINAR

EDUCATIONAL SEMINAR AFTERNOON SESSION
(Sibley/Diamond Rooms)
MODERATOR: Jodee Pring, Board Member Wyoming Water Association, Cheyenne, WY

1:30 p.m. **Peter Gill,** Project Manager, Wyoming Water Development Office, Cheyenne, WY and **Jim Vanderweide**, Trihydro Corporation, Laramie, WY. "Simplified GIS Requirements: New Data Models and Standards for Future WWDC Projects."

2:10 p.m. **Rosemary Hatch**, Outreach & Technology Coordinator, Water Resources Data System (WRDS), University of Wyoming, Laramie, WY, "Wyoming Water & Climate Atlas and WACnet"

Dave Myer, Project Manager, Wyoming Water Development Office, Cheyenne, WY, "A Unified Front Door to Wyoming's Instream Flow Data"

EDUCATIONAL SEMINAR AFTERNOON SESSION CONTINUED

3:00 p.m. AFTERNOON BREAK (Foyer)

3:15 p.m. **Teal Wyckoff**, WYGISC, "Introduction to the Natural Resource and Energy Explorer (NREX) and the Wyoming Geospatial Hub (GeoHub)"

4:00 p.m. **Megan Burke**, RESPEC, "Municipal Watershed Wildfire Hazard Mitigation Assessment"

5:00 p.m. ADJOURN (Dinner on your own)

FRIDAY, October 27

7:00 - 8:00 a.m. CONTINENTAL BREAKFAST

EDUCATIONAL SEMINAR MORNING SESSION
MODERATOR: Greg Kerr, Advisor Wyoming Water Association, Cheyenne, WY

8:00 a.m. **Ye Zhang**, Associate Professor, UW Geology & Geophysics, Laramie, WY "Hydrological Connectivity in the Laramie Range: Implication for Water Resources Management"

8:45 a.m. **Noriaki Ohara**, Assistant Professor, UW Civil and Architectural Engineering, Laramie, WY. "Field Study on Flow Paths in a Snow Covered Hillslope in the Snowy Range in Southeastern Wyoming"

9:30 a.m. **Beth Callaway**, River Basin Coordinator, Interstate Streams Division, Wyoming State Engineer's Office, Cheyenne, WY, "Wyoming Water Administration: An Overview of Interstate Compacts and Regulation"

10:15 a.m. MORNING BREAK (Foyer)

10:30 a.m. **Ginger Paige,** Associate Professor, Water Resources, UW Dept. of Ecosystem Science and Management, Laramie Wyoming, "WyCEHG: Building Capacity in Hydrology and Geophysics in Wyoming"

11:15 a.m. CLOSING REMARKS/DISTRIBUTE CERTIFICATES

11:30 a.m. ADJOURN

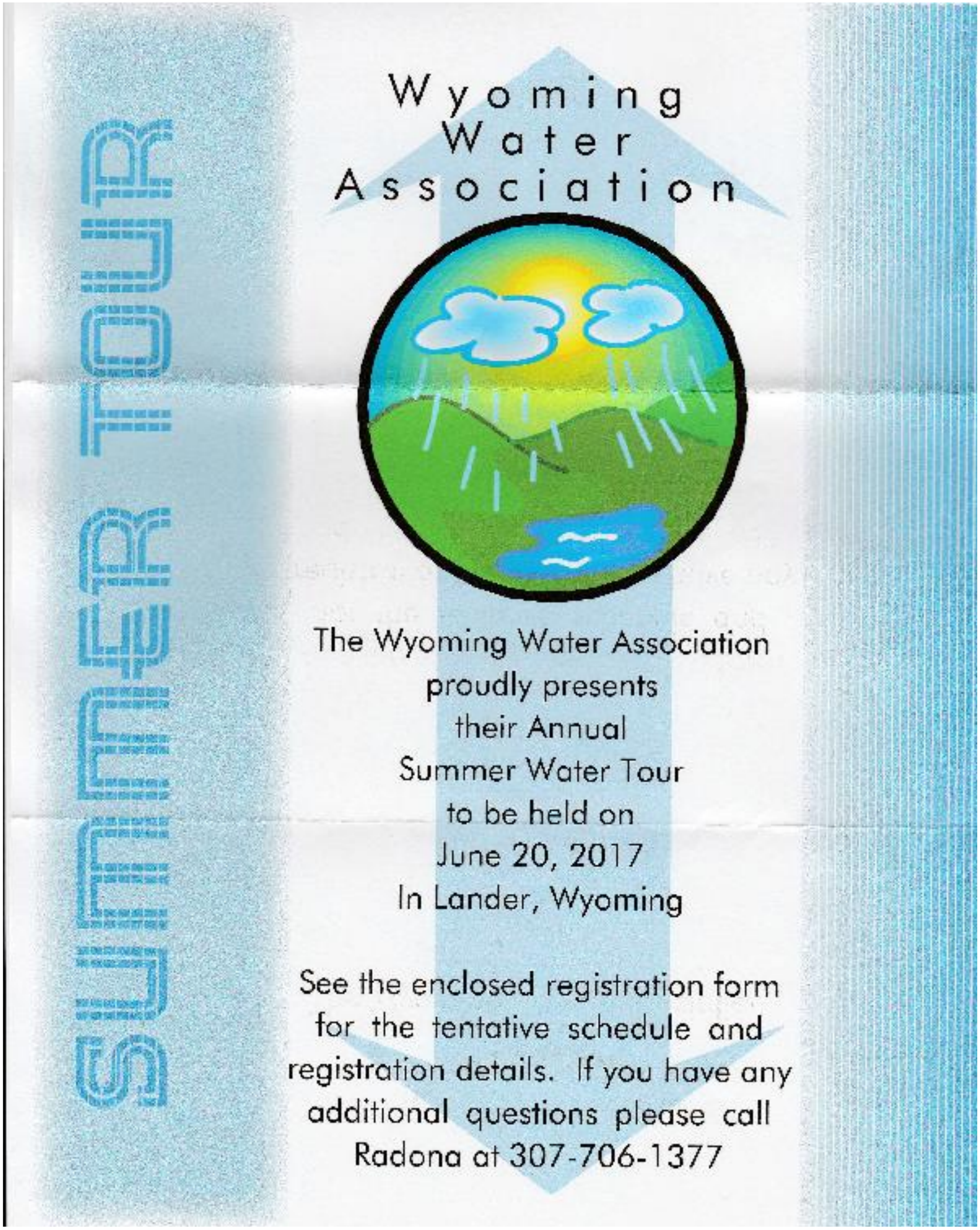
Wyoming Water Association 2017 Annual Meeting & Educational Seminar

With Special Thanks To:

Anderson Consulting
Water Resources Data Systems
True North Steel
Sunrise Engineering Inc
Energy Laboratories
Dynotek, LLC

On behalf of the Wyoming Water Association, the University of Wyoming Office of Water Programs, and the Upper Missouri Water Associations, we thank you for attending the 2017 Joint Annual Meeting and Educational Seminar.

Wyoming Water Association 2017 Summer Water Tour Program



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9:00	Meet at Safeway Parking lot/Depart for Fort Washakie

9:30	Arrive Fort Washakie
	• Meet with Mitch Contenoir, Tribal Water Engineer
	  o Discussion about current storage studies and drought management tools
	  o Site visit to recently completed diversion projects on S Fork Little Wind

12:00	Lander City Park
	• Lunch with Senator Case to discuss water issues in the Lander area (confirmed)
	• Meet with Conservation District, The Nature Conservancy, Wyoming Game and Fish Department
	  o Discussion and site visit of complete and ongoing restoration projects on the Middle Popo Agie
	  o Discussion about the Popo Agie Healthy River Initiative

2:00	Arrive Lander City Water Treatment Plant • Tour and discussion about potential enlargement (pending)
3:30	Optional trip to Sinks Canyon

Other Water-Related Activities of the OWP Director

These include, but may not be limited to these in a given year, the Wyoming Stock Growers, Wyoming Governor's Water Strategy Group, Wyoming State Legislature House and Senate Agriculture Committees, University of Wyoming Water Interest Group, and Wyoming Center for Environmental Hydrology and Geophysics Water Interest Group. The OWP Director attends meetings/presents on a random schedule (a FY17 list is given below) with these various water groups. The OWP occasionally co-sponsors selected meetings/conferences.

- AGU Fall Meeting, PI presentations on Wyoming Water Research Institute projects. New Orleans, LA., December 11-15, 2017.
- Wyoming State Legislature – Senate Agriculture Committee. Wyoming Water Development Commission (Advisor), Omnibus Water Plan/WRP FY2017 Proposals. State Legislature Bld., Cheyenne, WY., February 15, 2018.
- Wyoming State Legislature – House Agriculture Committee. Wyoming Water Development Commission (Advisor), Omnibus Water Plan/WRP FY2017 Proposals. State Legislature Bld., Cheyenne, WY., February 21, 2018.

Information Transfer Activities of Project PIs

Activities include those of PIs and students of ongoing and completed WRP funded research projects and other closely related water research and education projects. Includes support for peer publications and conference and meeting presentations for PIs and students of ongoing and completed WRP funded research projects and other closely related projects. Publications are listed in the individual research reports.

FY17 Presentations for **Project 2015WY88B**: "High-Resolution Modeling of Precipitation, Snowpack, and Streamflow in Wyoming: Quantifying Water Supply Variations in Future Decades", Bart Geerts, Atmospheric Science, UW.

- Geerts, B., 2017: Assessment of gridded precipitation estimates in the Greater Yellowstone Area using a Regional Climate Simulation, and changes in precipitation and snowpack in a changing climate. Yellowstone River Compact Technical Committee, Thermopolis, 6 April.
- Geerts, B., 2017: Assessment of gridded precipitation estimates in Wyoming using a Regional Climate Simulation, and changes in precipitation and snowpack in a changing climate. Spring 2017 Wyoming Water Forum, Cheyenne, 11 April.
- Geerts, B., and Y. Wang, and X. Jing: Assessment of Gridded Precipitation Estimates in the Interior Western United States using a Regional Climate Simulation. Presented at the 2017 Western Snow Conference, 17-19 April, Boise ID. (https://westernsnowconference.org/files/2017WSC-Agenda.pdf)
- Wang, Y., 2017: Precipitation and snowpack dynamics over mountains in the interior Western US in a changing global climate. Presented as a seminar at the South-Central Climate Science Center, July 2017.

FY17 Presentations for **Project 2015WY89B**: "Quantifying Return Flow in the Upper Wind River Basin", Ginger Paige and Scott Miller, Ecosystem Science and Management, UW.

- Claes, N., G.B. Paige, A. Parsekian, S.N. Miller, E. Kempema. 2017. Quantifying Return Flow in the Upper Wind River Basin. WyCEHG 3rd Water Interest Group Meeting, Laramie, WY. October 30, 2017.
- Claes, N., G.B. Paige, A. Parsekian, B. Gordon, S.N. Miller, J. Cook. 2017. Identification of surface and subsurface flow paths affecting return flow: merging hydrology and geophysics. UCOWR/NIWR Annual Meeting 2017. Fort Collins, CO. June 13-15, 2017.
- Claes, N., G.B. Paige, A. Parsekian. 2017. Identification of flow paths and quantification of return flow volumes and timing at field scale. American Geophysical Union Fall Meeting, New Orleans, LA December 15-18, 2017. *poster presentation*
- Claes, N., G.B. Paige, A. Parsekian, B. Gordon, S.N. Miller, J. Cook. 2017. Identifying flow barriers and subsurface flow paths affecting return flow. Symposium on the Application of Geophysics to Engineering and Environmental Problems, Denver, CO, March 19 - 23, 2017. *oral presentation*

FY17 Presentations for **Project 2016WY91B**: "Groundwater Modeling of the Casper Aquifer, Belvoir Ranch, Cheyenne", Ye Zhang, Geology & Geophysics, UW.

- Fangyu Gao†, Ye Zhang (2017) Simultaneous estimation of aquifer thickness, conductivity, and BC using borehole and hydrodynamic data with geostatistical inverse direct method, AGU Annual Meeting, New Orleans, Louisiana, poster presentation.
- Fangyu Gao†, Ye Zhang (2017) Applying spectral data analysis techniques to infer aquifer properties in Belvoir Ranch, Wyoming, AGU Annual Meeting, New Orleans, Louisiana, poster presentation.
- Fangyu Gao†, Ye Zhang (2017) A new inverse method for the simultaneous estimation of aquifer thickness and boundary conditions based on borehole and hydrodynamic measurements, AGU Hydro Days, Fort Collins, CO, March 20 – 22, 2017, oral presentation.

FY17 Presentations for **Project 2016WY92B**: "A New Multifunctional Sorbent for the Treatment of Coproduced Waters from the Energy Industry", Maohong Fan, School of Energy Resources and Dept. of Chemical & Petroleum Eng., UW.

- Andrew T. Jacobson (2017, August) *A New Multifunctional Sorbent for the Treatment of Coproduced Waters (CWs) from the Energy Industry*. Presented at Wyoming Water Development Commission Office, Cheyenne, WY.
- Andrew T. Jacobson (2018, May) *Evaluation and Development of Solid Adsorbents for Water Remediation.* Presented at PhD Preliminary Examination, Laramie, WY.

FY17 Presentations for **Project 2016WY93B**: "Produced Water Treatment with Smart Materials for Reuse in Energy Exploration", Dongmei (Katie) Li, Dept. of Chemical Engineering, UW.

- North American Membrane Society (NAMS) (May, 2016)
- American Institute of Chemical Engineers (AIChE) (November, 2016)
- Material Science and Engineering Symposium poster session (April, 2017)
- International Congress on Membranes and Membrane Processes (ICOM) (July-August, 2017)
- American Chemistry Society (ACS) (March, 2018)
- Material Science and Engineering Symposium poster session (March, 2018)

FY17 Presentations and Conferences for **non-104 Institute Contract**: “Economic Assessment of Alternative Groundwater Management Strategies in Laramie County”, funded by Wyoming Water Development Commission Contract, Kristiana Hansen and Dannele Peck, Agricultural & Applied Economics; and Scott Miller, UW.

- Willis, K., K. Hansen, D. Peck and S. Glendenning. 2017. “Water Use and Management in Laramie County, WY.” Invited poster presentation at the UW Extension 2017 Organic Farming Conference. Cheyenne, WY (February 2017). Presentation by K. Willis.
- Hansen, K., D. Peck, and K. Willis. “Alternative Groundwater Management Strategies over the Ogallala Aquifer in Southeastern Wyoming. Invited presentation at the Universities Council on Water Resources Annual Meeting. Fort Collins, CO (June 2017). Presentation by D. Peck.
- Ms. Willis and Dr. Hansen attended the Laramie County Organic Farming Conference, hosted by University of Wyoming Extension (Cheyenne, WY; February 22-23, 2017). Ms. Willis gave a presentation.
- Dr. Hansen attended the Daugherty Water for Food Institute Global Water Conference at University of Nebraska, Lincoln to give a presentation on a different water-related research project (Lincoln, NE; April 2017). (Travel supported by another funding source.)
- Ms. Willis and Dr. Peck will attend the Universities Council on Water Resources Annual meeting (Fort Collins, CO; prospective, CO, June 2017).
- Ms. Willis and Dr. Hansen attended the Ogallala Aquifer Summit (Garden City, KS; April 9-10, 2018). Ms. Willis and Dr. Hansen made connections with researchers, policymakers, and producers in other states overlying the Ogallala that will benefit the research project as well as UW’s capacity to work on groundwater management problems in Wyoming moving forward.

<u>OWP Web Site</u>

The OWP maintains a basic web site which includes the most recent request for proposals and project reports. The web site address is uwyo.edu/owp.

USGS Summer Intern Program

None.

Student Support					
Category	**Section 104 Base Grant**	**Section 104 NCGP Award**	**NIWR-USGS Internship**	**Supplemental Awards**	**Total**
Undergraduate	8	0	0	0	8
Masters	3	0	0	1	4
Ph.D.	7	0	0	0	7
Post-Doc.	1	0	0	0	1
Total	19	0	0	1	20

Notable Awards and Achievements

Project 2015WY89B. “Quantifying Return Flow in the Upper Wind River Basin”, Ginger Paige and Scott Miller, Ecosystem Science and Management, UW. This project has leveraged additional support from two funding sources to expand the instrumentation and provide additional funding to support graduate student research: 1. Wyoming Center for Environmental Hydrology and Geophysics (WyCEHG, (NSF EPS-1208909)). 2. Walton Foundation (through the Haub School of Environment and Natural Resources, University of Wyoming) provided funding for MS graduate student Bea Gordon.

Project 2016WY93B: “Produced Water Treatment with Smart Materials for Reuse in Energy Exploration”, Dongmei (Katie) Li, Dept. of Chemical Engineering, UW. Audra DeStefano, MS student, won the super competitive Elia Klein Travel award that is given to graduate students worldwide in 2016, which partially funded her trip to present a poster at North American Membrane Society (NAMS) annual meeting held in Bellevue, WA, May, 2016 (not reported last year).

Project 2016WY93B: “Produced Water Treatment with Smart Materials for Reuse in Energy Exploration”, Dongmei (Katie) Li, Dept. of Chemical Engineering, UW. Audra DeStefano, MS student, was nominated as Own It! outstanding female undergraduate in Spring 2016 (not reported last year).

Project 2016WY93B: “Produced Water Treatment with Smart Materials for Reuse in Energy Exploration”, Dongmei (Katie) Li, Dept. of Chemical Engineering, UW. Audra Destefan, MS student, was awarded 2016-17 Mountain West Scholar-Athlete of the Year for her exceptional athletic, academic accomplishments and community services (not reported last year).

Publications from Prior Years

1. 2015WY88B ("High-Resolution Modeling of Precipitation, Snowpack, and Streamflow in Wyoming: Quantifying Water Supply Variations in Future Decades") - Articles in Refereed Scientific Journals - Jing, X., B. Geerts, Y. Wang, and C. Liu, 2017: Regional Climate Simulation of Orographic Precipitation in the Interior Western United States: Comparisons with Gauge and High-Resolution Gridded Datasets. J. Hydromet., 18, 2541–2558. https://doi.org/10.1175/JHM-D-17-0056.1