Wyoming Water Research Program
Annual Technical Report
FY 2016

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 Annual Report: “Quantifying Return Flow in the Upper Wind River Basin”, Ginger Paige and Scott Miller, Ecosystem Science and Management, UW, Mar 2015 – Feb 2018.

Project 2016WY91B Annual Report: “Groundwater Modeling of the Casper Aquifer, Belvoir Ranch, Cheyenne”, Ye Zhang, Geology & Geophysics, UW, Mar 2015 – Feb 2018.

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:	3/1/2015
End Date:	2/28/2017
Funding Source:	104B
Congressional District:	1
Research Category:	Climate and Hydrologic Processes
Focus Category:	Water Quantity, Climatological Processes, Hydrology
Descriptors:	None
Principal Investigators:	Bart Geerts

Publications

There are no publications.

Final grant report:
High-resolution modeling of precipitation, snowpack, and streamflow in Wyoming: quantifying water supply variations in future decades

Bart Geerts, PI
Yonggang Wang, co-PI

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.

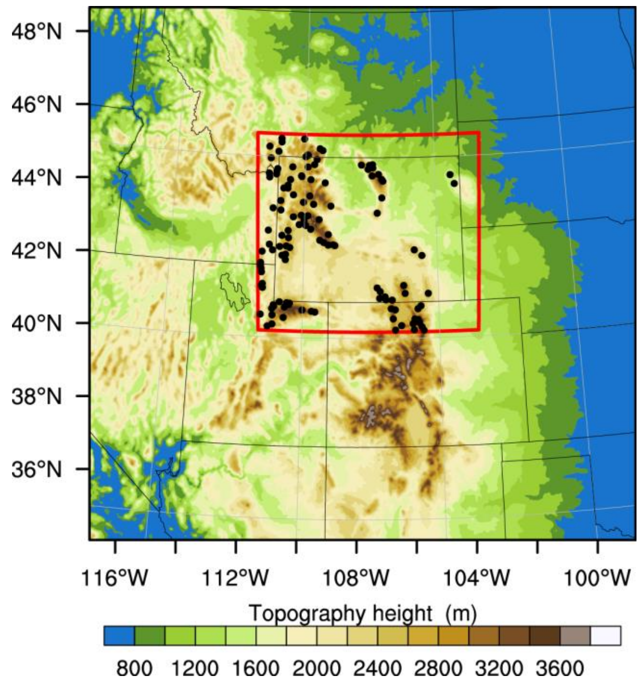

Fig. 1: Model domain of the 4-km regional climate simulation. The black dots are SNOTEL sites within Wyoming and vicinity.

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 $0.5^o \times 0.5^o$ 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.

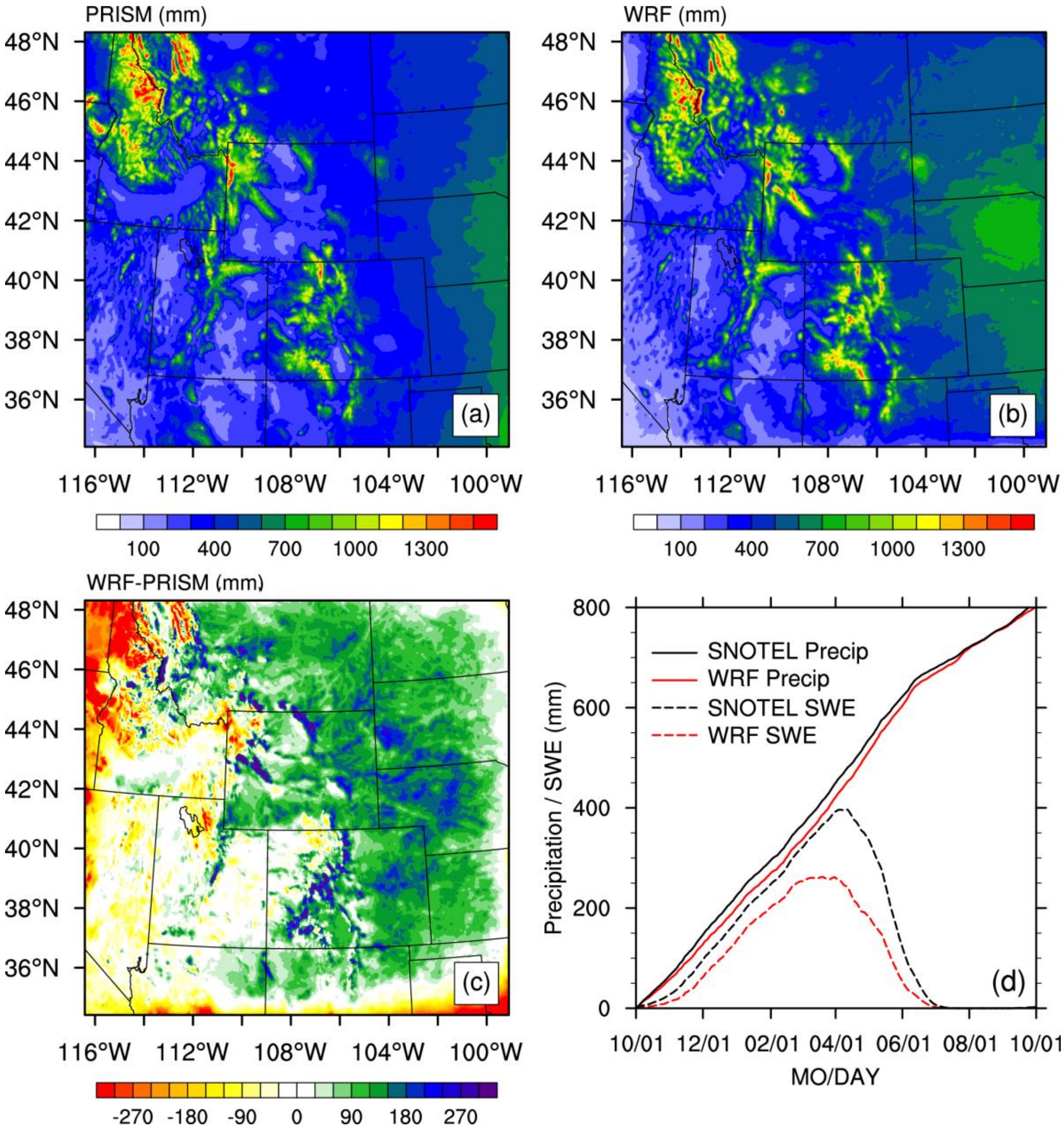

Fig. 2. Evaluation of 30 years of WRF (3.7.1) simulations. (a) PRISM annual precipitation; (b) WRF annual precipitation; (c) absolute difference between (b) and (a); (d) average seasonal precipitation accumulation and snowpack SWE at all SNOTEL sites shown in Fig. 1 as modelled (WRF) and observed (SNOTEL).

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).

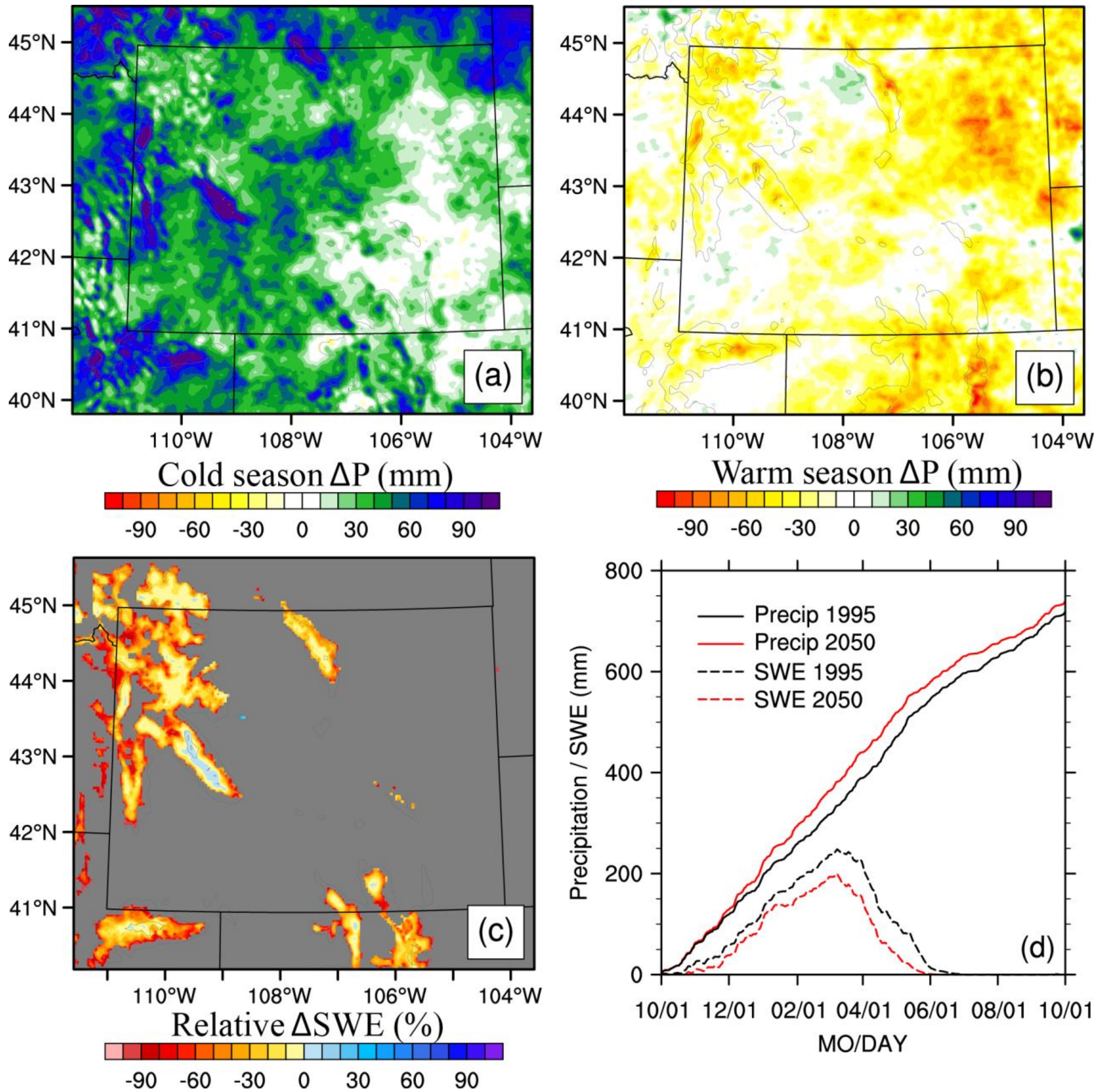

Fig. 3. Comparison of 30 years of retrospective and PGW simulations over Wyoming and vicinity. (a) The 30-yr average difference of precipitation during the cold season (future minus current); (b) same as (a), but for warm season; (c) the 30-yr average difference of SWE on 1 April (future minus current); (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

Wang, Y., B. Geerts, and C. Liu, 2017a: Retrospective high-resolution regional climate simulations over interior Western US: validation of fine-scale patterns of precipitation and snowpack over complex terrain. *J. Climate*, in review.

Jing, X, B. Geerts, Y. Wang and C. Liu, 2017: Assessment of Gridded Precipitation Estimates in the Interior Western United States using a Regional Climate Simulation. *J. Hydrometeorology*, in review. [only minor revisions required]

Wang, Y., B. Geerts, and C. Liu, 2017b: Changing precipitation and snowpack dynamics over US northern Rockies in a changing climate: insights from high-resolution WRF simulations. *J. Appl. Meteor. 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)

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:	3/1/2016
End Date:	2/28/2018
Funding Source:	104B
Congressional District:	1
Research Category:	Climate and Hydrologic Processes
Focus Category:	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.

Quantifying Return Flow in the Upper Wind River Basin
Update Report: June 2014 – February 2017

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.

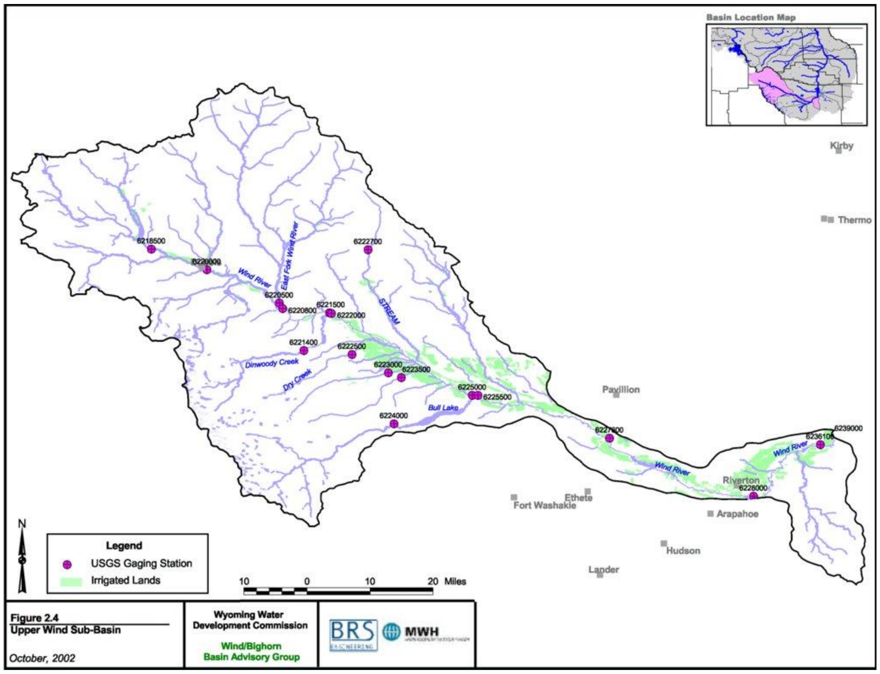

Figure 1. Location of the East Fork in the Upper Wind River Sub-Basin (courtesy: Wyoming Water Development Office *http://waterplan.state.wy.us/plan/bighorn/*)

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.

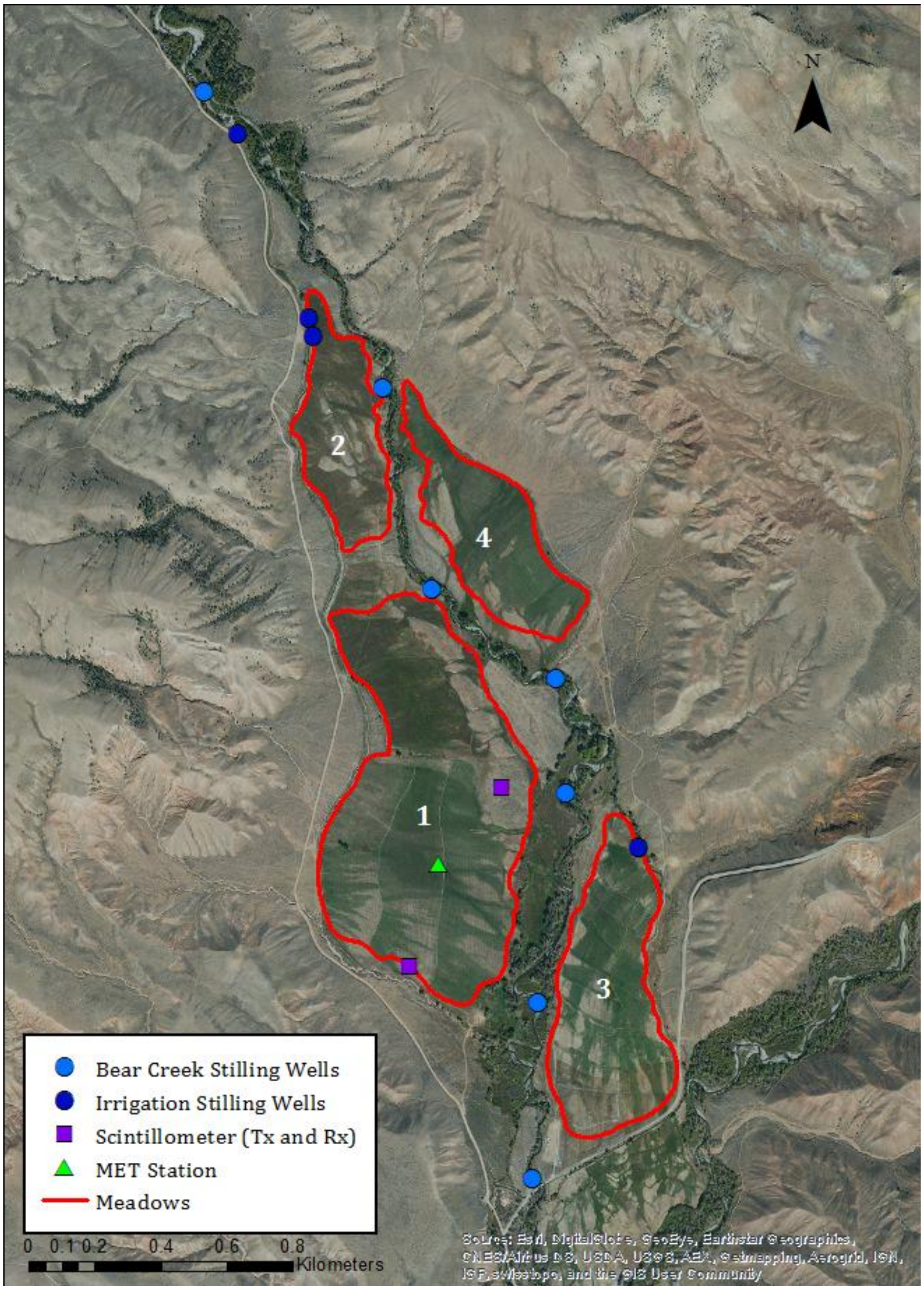

Figure 2. Location of installed instrumentation relative to irrigated meadows and stream.

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).

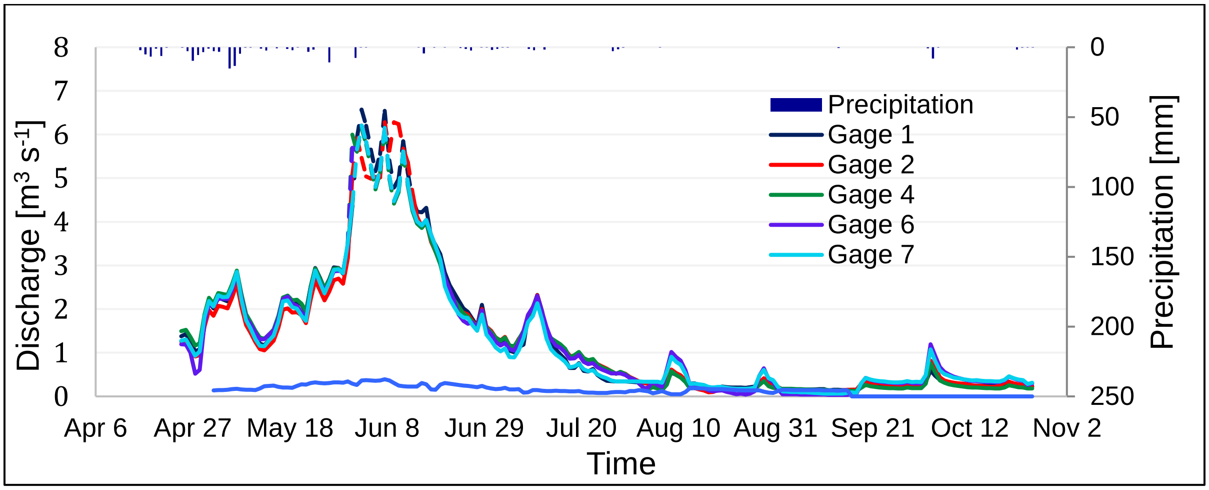

Figure 3. Seasonal hydrographs, precipitation and irrigation from all sites (2015).

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.

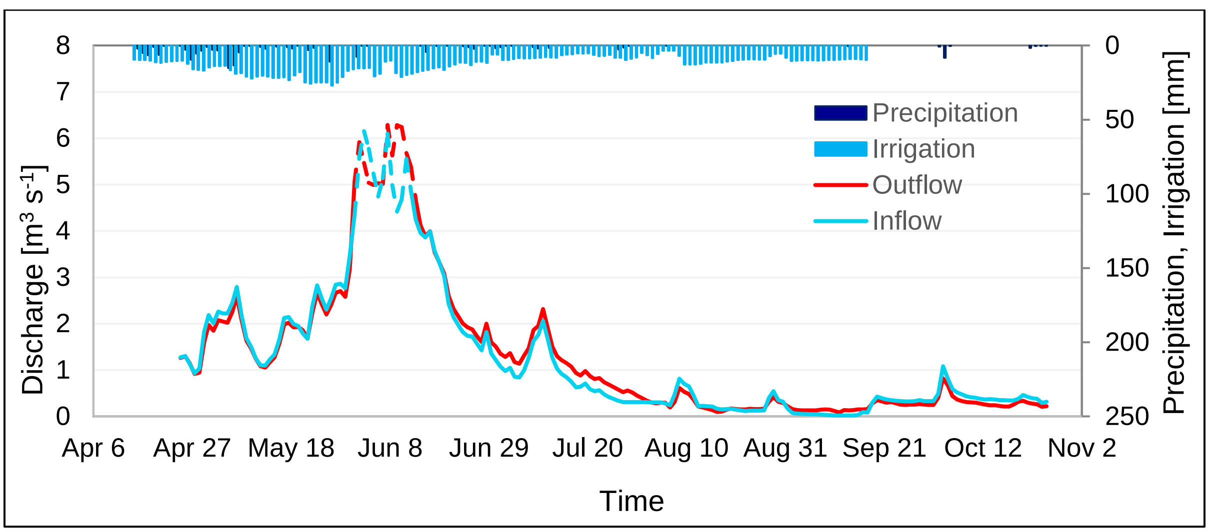

Figure 4. Inflow and outflow hydrographs used to calculate return flow (Q_{RT}).

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).

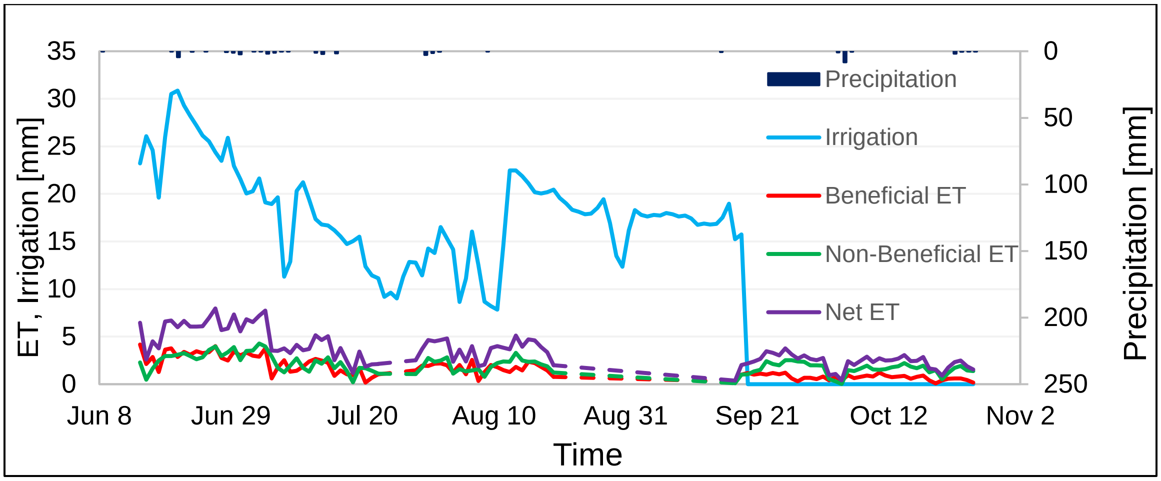

Figure 5. Evapotranspiration for the 2015 irrigation season. Non-beneficial ET is the evapotranspiration for the riparian areas calculated from using Penman-Montheith. Beneficial ET was calculated from the scintillometer.

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.

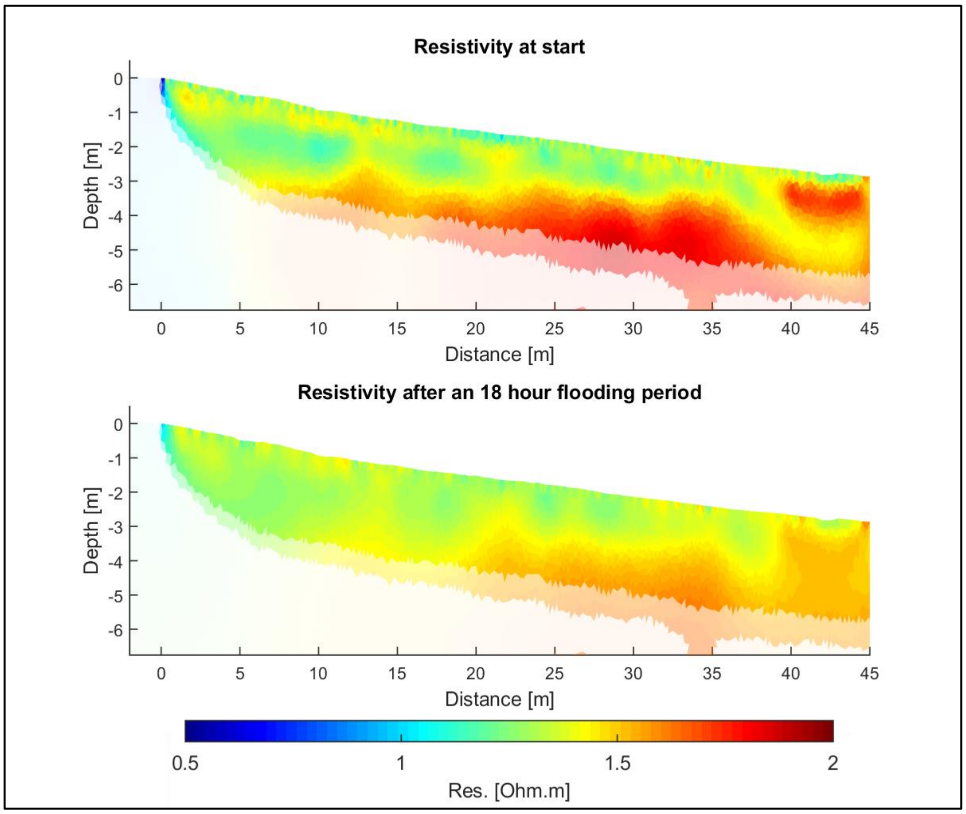

Figure 6. Time Lapse ERT during wetting and drying (before, during and after irrigation applications).

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.)

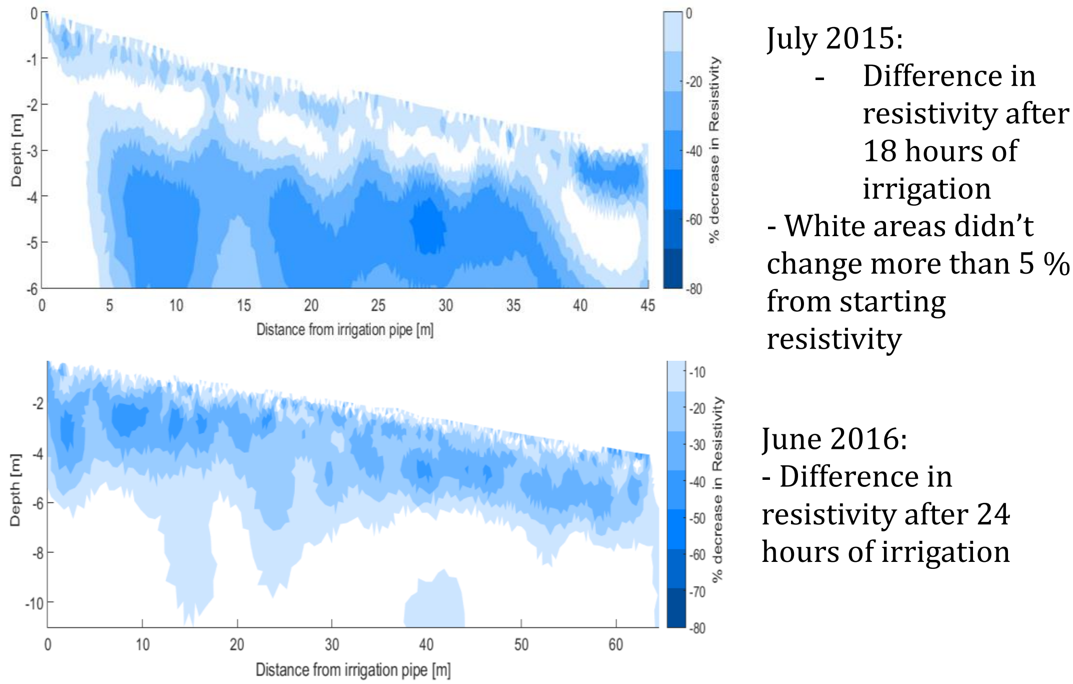

Figure 7. Comparison of time-lapse resistivity during irrigation experiments in 2015 and 2016. The changes in resistivity are being converted to changes in water content.

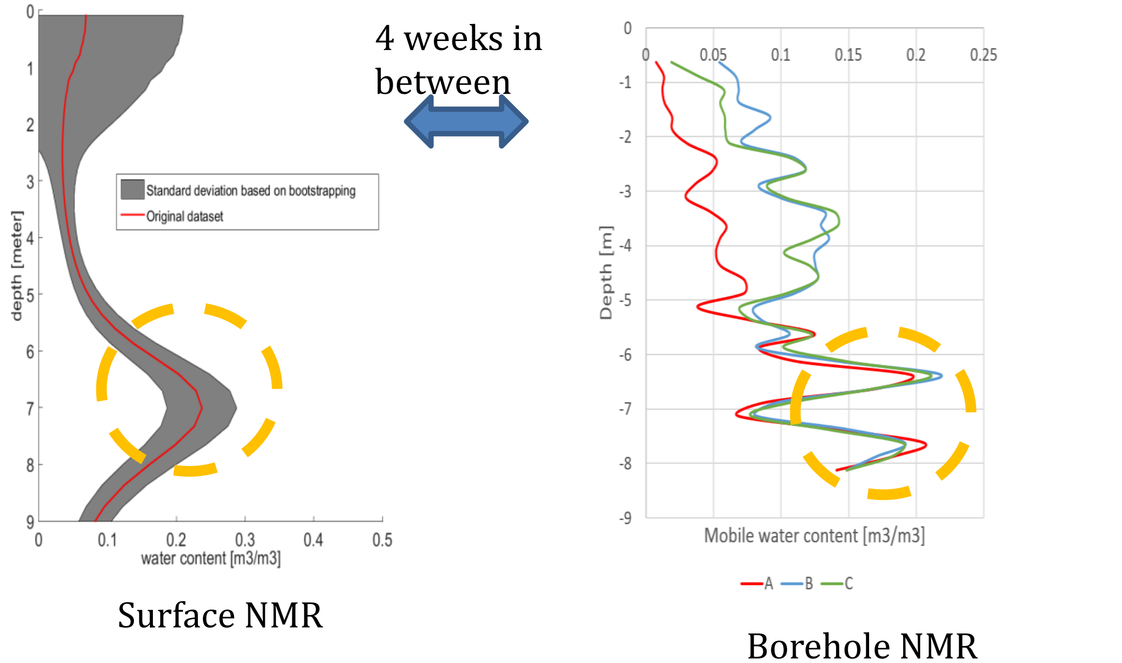

Figure 8. Comparison of results from surface NMR and time- borehole NMR showing water content increasing at the same depth in the subsurface.

Next Steps:
For the upcoming 2017 irrigation season, we will continue to measure the components of the water balance.

In addition, we will:

- Continue and expand ET measurements
- Continue and expand geophysical measurements
- Conduct intensive field scale studies using time-lapse ERT (MPT) on multiple fields
- Continue to use the network of boreholes to monitor subsurface flow using time-lapse borehole NMR to track soil water in the subsurface.

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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).

Presentations:
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)

Parsekian A.D., Paige, G.B., Miller S.N., Gordon B.L., Claes, N. 2015. Return flow: untangling the water budget on flood-irrigated fields. 2015 Water Interest Group Meeting, Oct. 13, 2015, Laramie, WY. (invited presentation)

Gordon, B.L., Miller, S.N., Paige, G.B, Claes, N., Parsekian, A., Beverly, D. 2015. A Comparison of Methods for Calculating Evapotranspiration in a Semi-Arid Agricultural System, 2015 AGU Fall Meeting, December 14-18, 2015, San Francisco, CA. (poster)

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)

Gordon, B.L., Miller, S.N., Paige, G.B, Claes, N., Parsekian, A., Beverly, D. 2015. Calculating Return Flows and Consumptive Use in a Semi-Arid Agricultural System, 2015 Water Interest Group Meeting, Oct. 13. 2015, Laramie, WY. (poster)

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Claes, N., Paige, G.B, Parsekian, A. D., Miller, S. N., Gordon, B. L., 2015. Characterization of flood irrigation: merging hydrology and geophysics. WyCEHG Water Interest Group and Wyoming Round-Up, 2015, 14th October, Laramie, WY. (poster)

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:
Gordon, B.L. (2014), *Measuring return flows*. Western Confluence Magazine Vol. 1, Ruckelshaus Institute, Laramie WY.

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

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. 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)

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:	3/1/2016
End Date:	2/28/2018
Funding Source:	104B
Congressional District:	1
Research Category:	Ground-water Flow and Transport
Focus Category:	Groundwater, Models, Water Supply
Descriptors:	None
Principal Investigators:	Ye Zhang

Publications

There are no publications.

Groundwater Modeling of the Casper Aquifer, Belvoir Ranch, Cheyenne
FY16 Annual Report

1. Abstract

To meet the future water demands, the Cheyenne Board of Public Utilities (BOPU) plans to develop the Casper Aquifer at the Belvoir Ranch, Cheyenne, as a groundwater resource. Despite several preliminary studies that evaluated and characterized the Casper Aquifer at this site, complex site hydrogeology precludes the development of a well-informed drilling plan, i.e., where future municipal water supply wells should be placed and the appropriate seasonal pumping rate, duration, and well rotation. To ensure sustainable well yields, water supply wells need to tap into aquifer regions with high hydraulic conductivity (K) that can also capture the natural recharge into the subsurface. However, uncertainty exists in the current understanding of groundwater flow in this aquifer due to several reasons: (1) aquifer geometry and K distribution are highly uncertain; (2) location, timing, and rate of aquifer recharge remain uncertain; (3) aquifer boundary conditions are uncertain, i.e., based on well test interpretation, the aquifer is intersected by several faults that range from impervious to conductive. To effectively manage this aquifer and to provide guidance for its sustainable development, these uncertainties must be reduced.

2. 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, folds, 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.

3. 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 hydro-structural 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 permeabilities [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 well capture zone analysis will be conducted to determine the pumping program (rate, duration, well rotation) that can best capture the natural recharge into the aquifer, while achieving sustainable water yields.

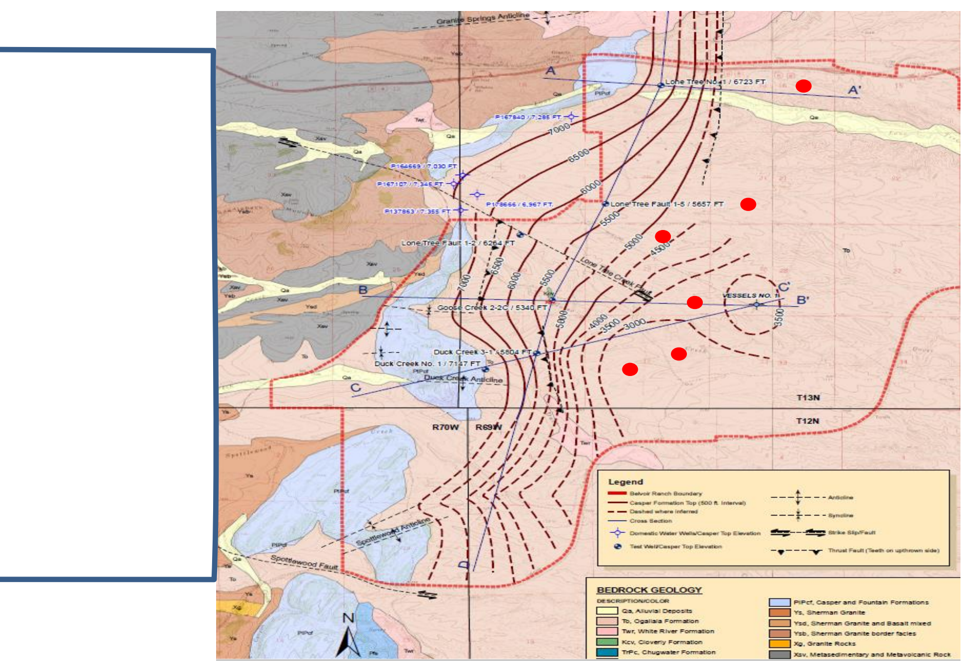


Figure1: Study area at the Belvoir Ranch with inferred subsurface structures in the Casper Aquifer. Locations of the aquifer outcrops are shown in light blue color. Locations of four hydrostratigraphic cross sections (A-A’, B-B’,C-C’, and D-D’) are shown. The modeling domain is shown by the blue outline. The ranch boundary is marked by the red outline.

4. 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.

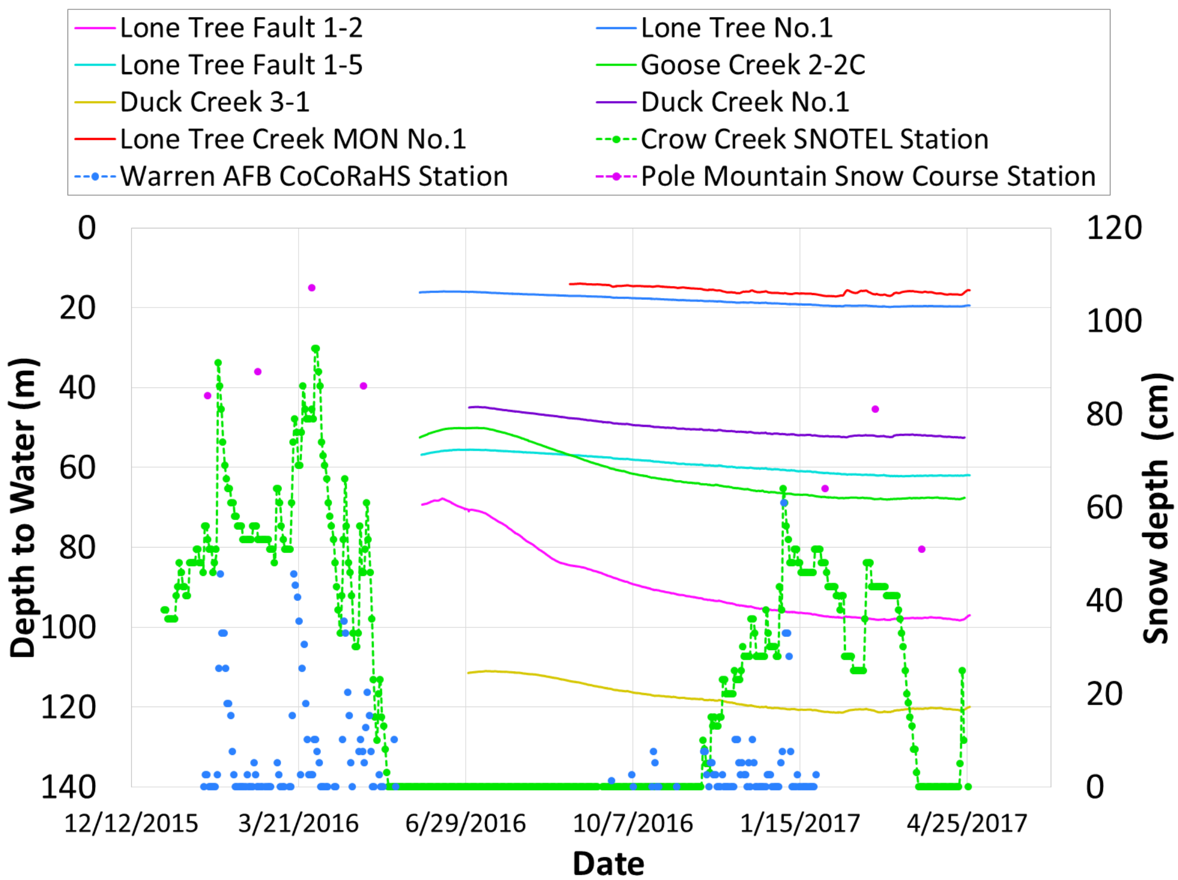
5. Progress to date including significance

5.1 Monitoring data acquisition

From June 6th to 8th, 2016, an additional Casper Aquifer monitoring 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. Longitude and Latitude 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 past pumping tests. 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 with a total well depth of 177 feet. After the well was developed, water level was measured at 46.18 feet from top of casing.

During the summer of 2016, all seven observation wells, including Lone Tree MON No. 1, were instrumented with In-Situ Level Troll transducers. Water level and temperature data are measured every thirty minutes at each well. These data are then sent by a telemetry system to an online server that can be accessed by the project team any time (passcode to the online server was also shared with water managers of BOPU in Cheyenne). Water level data, from the summer of 2016 to the current date, are plotted with snow depth data from three nearby SNOTEL and snow stations (Figure 2). Water level data will be used for model parameter, recharge, and boundary condition estimation.

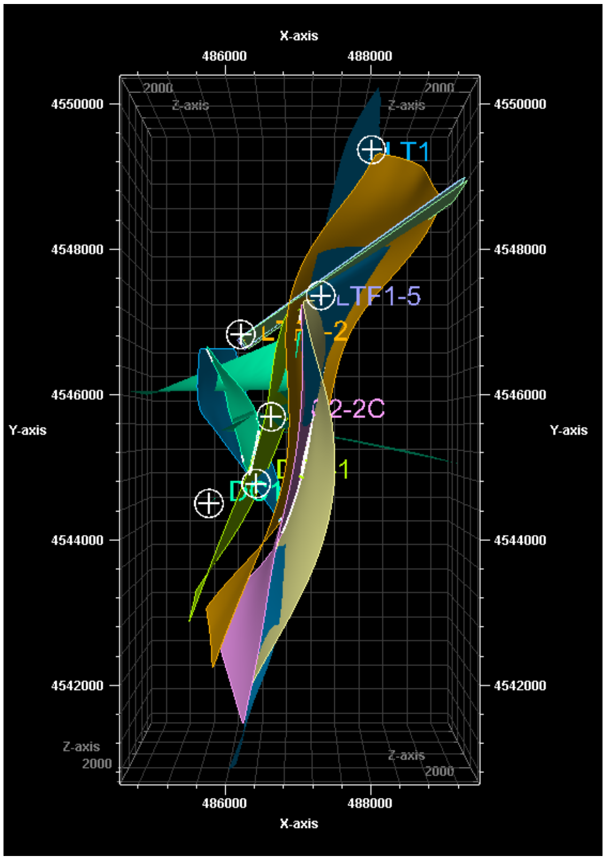
Figure 2: Plotted water level data with snow depth data



5.2 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. Because of the uncertainties of the model, multiple models with different geological features should be built, and final pumping plans will be given for each of the models. 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 2 is the draft fault model created with Petrel from last year's annual report.

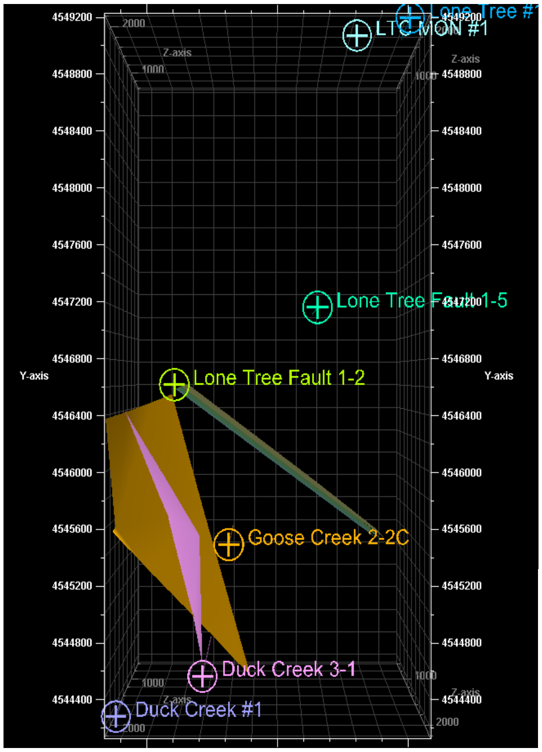
Figure 3: Fault model created by Petrel which is showing the major faults in the site area.



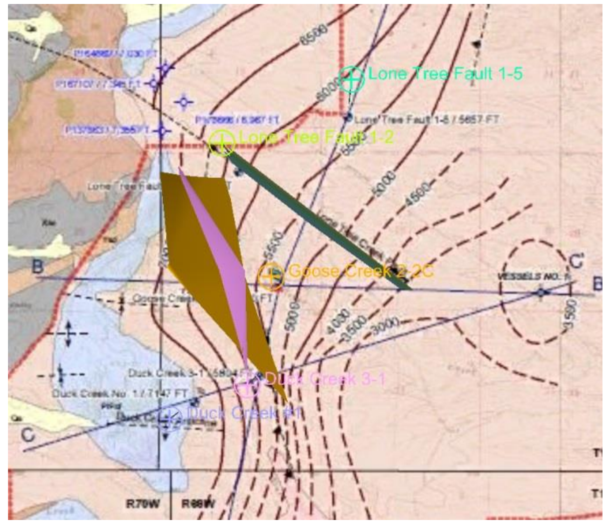
This year, a preliminary Petrel model was built to incorporate the three essential faults shown on the geologic map. The model built last year with very complex fault system only captures two of the three essential faults shown on the geologic map. Including all interpreted faults from seismic data is not necessarily the optimized option. Indeed, the model with three faults will be 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, so 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 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 identified in this study at the site area.



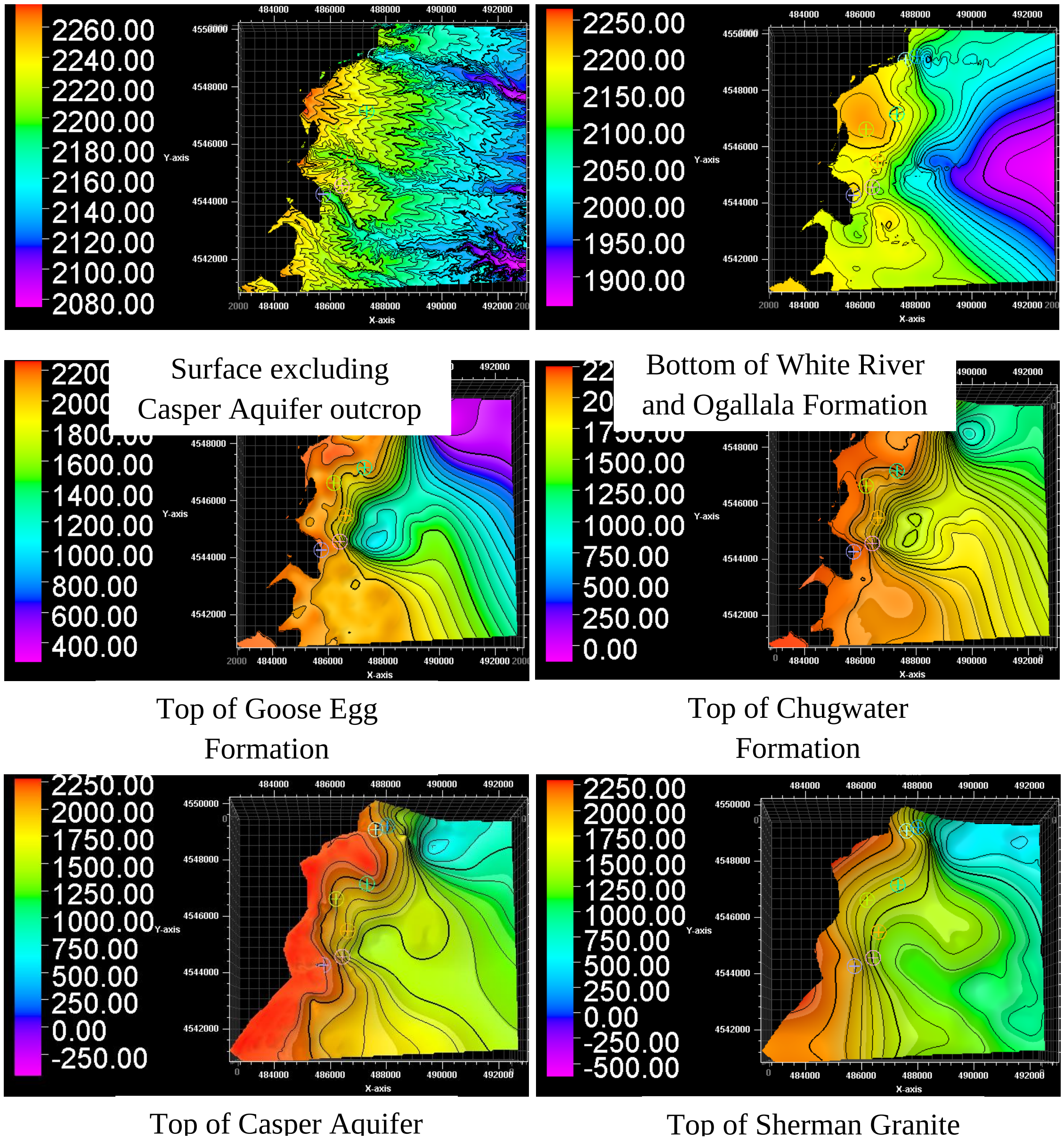
(a) Updated Petrel fault model



(b) Comparison between the geologic map and the updated fault model

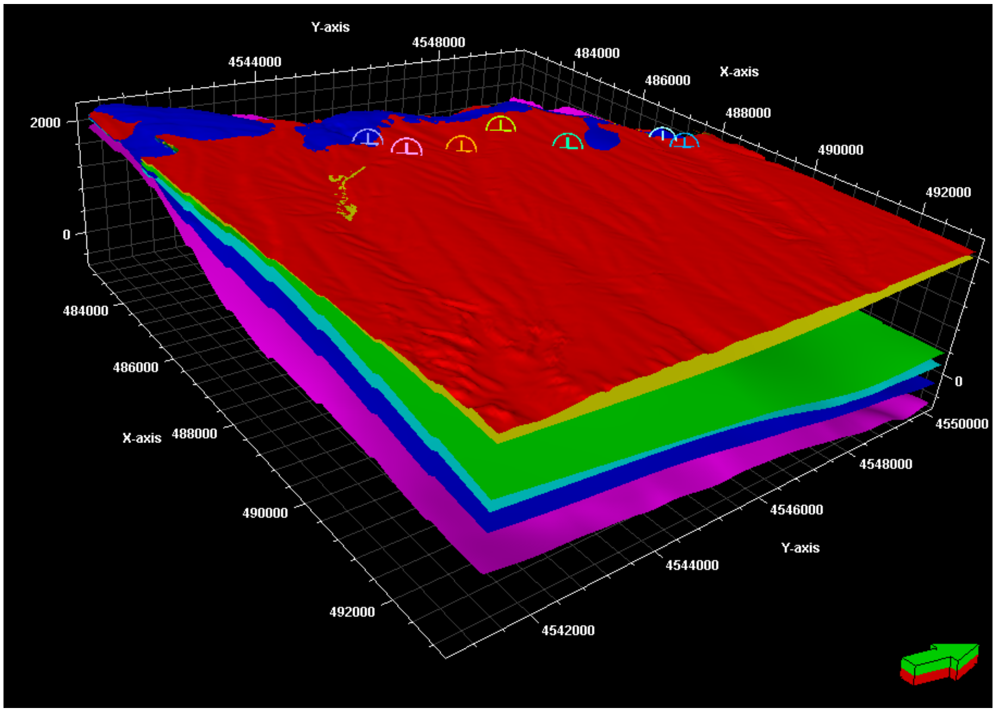
Bird's view map of each formation is shown in Figure 4. In this updated model, six horizons are made. First horizon is the surface excluding Casper Aquifer outcrop; second horizon is the bottom of either White River or Ogallala Formation, since they are the erosional formations; third horizon is top 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: Map view of each interpreted surface in *Petrel*.



The elevations of the formation tops were all verified with hard data. Figure 3 is the updated 3D integrated model with the formation tops. This Petrel model is not the final version of the static model because of the uncertainties in the geophysical data caused by human interpretation errors. This Petrel static model is exported to FEFLOW later for further parameter estimation work. A new inversion method developed by our group will also be used to inverse parameters such as hydraulic conductivities, boundary conditions, and Casper Formation thickness. Results of FePEST and the new inversion method will be compared, and a final pumping plan will be given from the analysis.

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

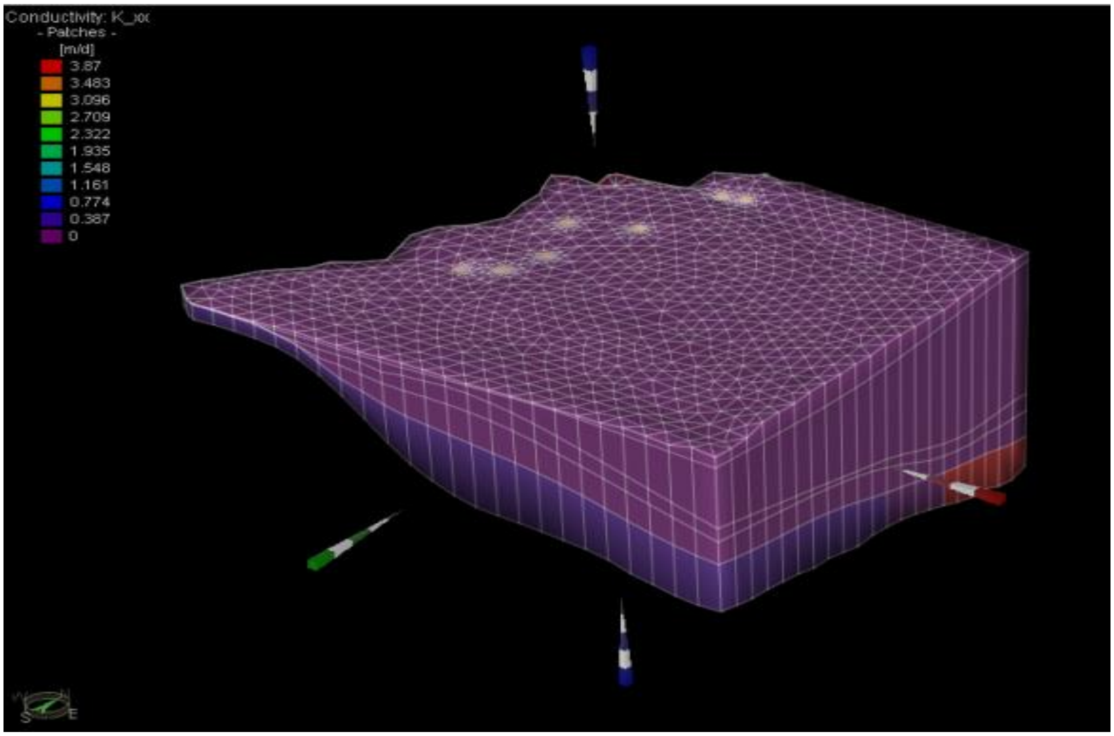


5.3 Parameter estimation

Last year, 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 with high error [7]. Thus, the model calibration work will be done using FEFLOW and FePEST instead of GWV and PEST. This simplified Petrel structural model is imported to FEFLOW as the base case of the forward model. Hydraulic parameters and boundary conditions are roughly assigned to the model. Initial hydraulic parameter estimations are from 2012 Lidstone final report [1]. The estimations have been verified by using Aqtesolv with historic pumping data. Boundary conditions are roughly assigned to the model based on water level contour map from recent monitoring well data collection.

The initial FEFLOW model is shown in Figure 7. Pumping history will be imported to FEFLOW for parameter estimation. After the hydraulic conductivities are inversed using FePEST for the base model, more structural models will be imported to FEFLOW for parameter estimation. Then, estimated parameters will be assigned to each forward structural model for pumping plan design and analysis.

Figure 7: FEFLOW hydrostratigraphic model with a set of preliminary hydraulic conductivities assigned to the model units. For groundwater modeling, each unit is further subdivided into multiple layers (not shown).



FePEST is not the only method used for parameter estimation. A new inverse method will be used for parameter estimation as well. This new inverse method is developed from our group, and has the capability of simultaneously inverse hydraulic conductivity, aquifer thickness, and boundary conditions. At this point of the development, the inverse method can handle steady-state ambient flow inversion with no artificial source/sink. The advantage of this new inversion method is, it doesn't need the development of a numerical forward model or estimation of the boundary conditions.

Before applying the new method to calibrate the structural models, the novel inverse method should be verified with a simple synthetic problem. An example code was written with MATLAB to solve a synthetic steady state 3D problem with no sinks/sources. The model is shown in Figure 4. In this model, there are 2 hydraulic conductivity (K) zones. Thickness of the aquifer is expressed as a function of x and y, and it is written as:

$$b(x, y) = 0.1 \times x + 0.05 \times y$$

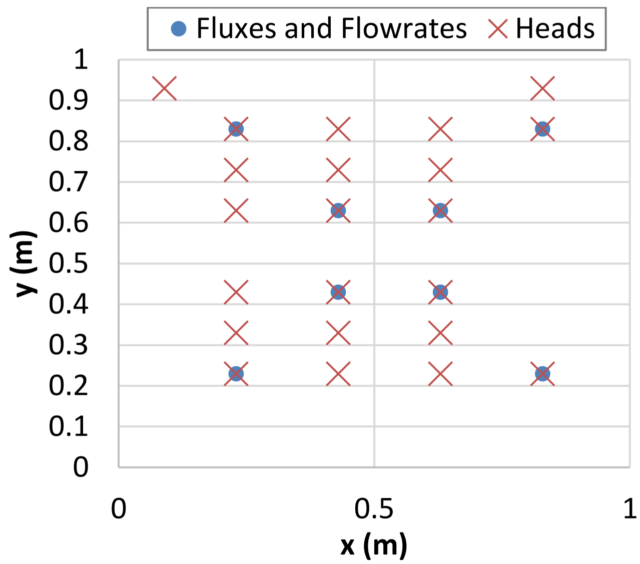
In zone 1, K is 1m/year, and in zone 2, K is 10 m/year. Figure 8 is showing the locations of observation data. 24 observation wells are represented by the red dot to give the head data. 8 observation wells are represented by the blue dot gives flux and flowrate data.

Two hydraulic contuctivities, boundary conditions, and thickness have been successfully in verted using the new inverse method. The inverted thickness of the aquifer is:

$$b(x, y) = 0.0991 \times x + 0.0505 \times y$$

Inverted K in zone 1 is 0.9976 m/yr, and that in zone 2 is 10.0887 m/yr. 2D head contour and BCs are successfully recovered.

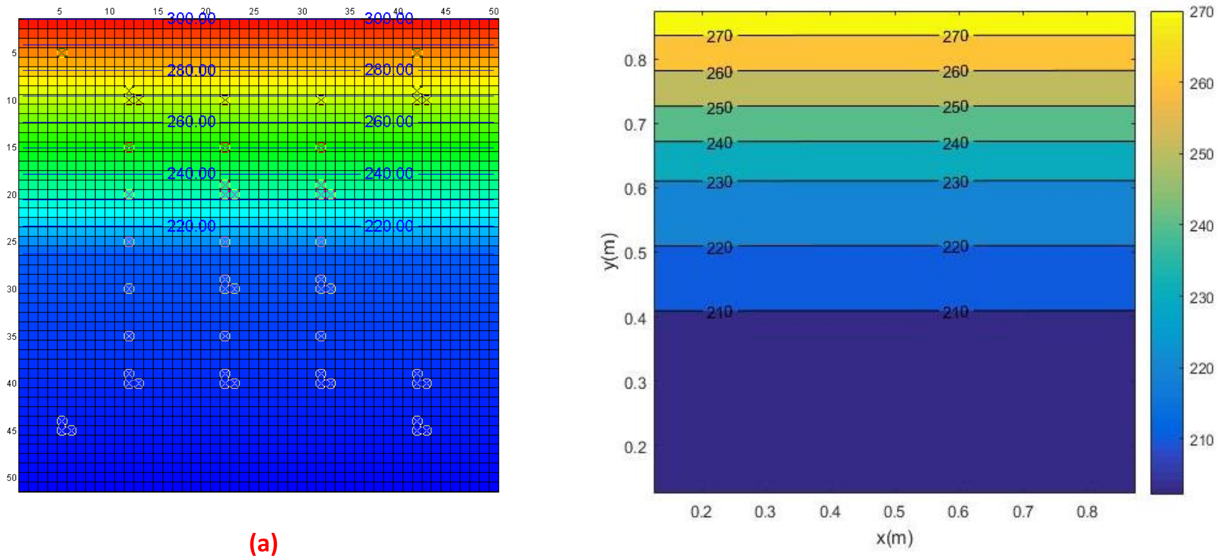
Figure 8: Forward model created with GWV to calculate observation data



By using the true values of Ks, BCs, and aquifer thickness, GWV can calculate the head map for the true model, and it is shown in Figure 9(a). Head map can be calculated with the inverted hydraulic conductivities and boundary conditions, and it is plotted in Figure 9(b). By comparing the true head map and inverted head map, we can find that the head map is recovered well by using the new inverse method: standard deviation of the mean estimation error is less than 5%.

Figure 9: (a) Head map of true model; (b) Inverted head map using new method

Next, unbiased errors are applied to the measurement locations (head, fluxes, and



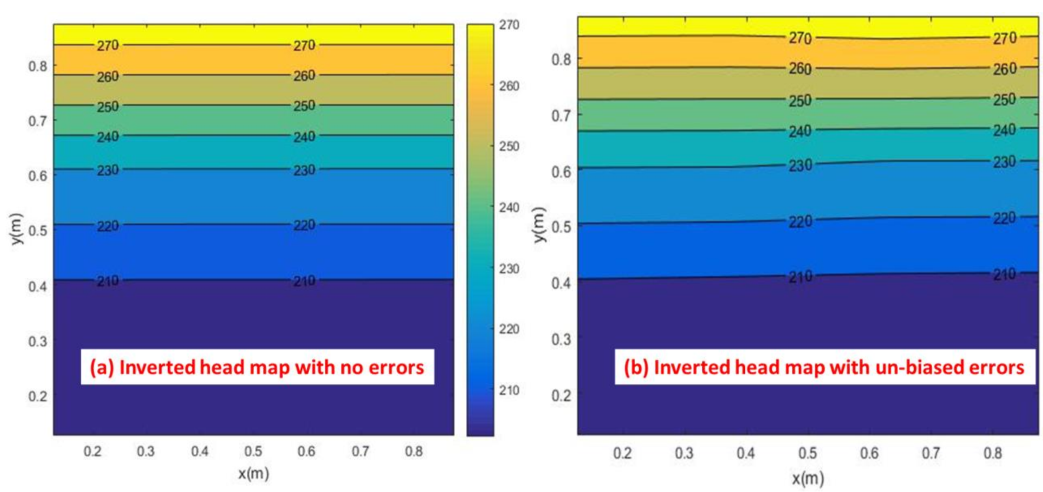
(a)

(b)

flowrates). In the study of inverse with measurement errors, +/- 10% unbiased errors are added to observation heads; +/- 15% unbiased errors are added to the observation fluxes and flowrates. Resulted thickness is :

$$b(x) = 0.0740 \times x + 0.0673 \times y$$

Inverted Ks for zone 1 and zone 2 are 0.9580 m/yr and 7.9699 m/yr respectively. Comparison between inverted head maps with and without measurement errors are presented in Figure 10(a) and (b). From the comparison, we can see that the inverses method can recover the head map with reasonable range of measurement errors.



(a) Inverted head map with no errors

(b) Inverted head map with un-biased errors

Currently, the new inversion method is being adapted for joint parameter, thickness, and boundary condition estimation with sources and sinks. After verifying the inverse method with the synthetic problem, we will apply the method to calibrating the Belvoir Ranch site model.

Significance

Modeling data-spare aquifer is challenging due to lack of information on aquifer geometry, parameters, and boundary conditions. Based on simulation studies of synthetic three-dimensional aquifers dominated by lateral flow, this research has developed a novel approach for joint aquifer parameter, thickness, and BC estimation. The method will be tested in modeling groundwater flow in the Casper Aquifer at Belvoir Ranch to help reduce uncertainty and improve model accuracy.

Plan for next year

Based on the calibration study conducted using a synthetic aquifer to jointly estimate its thickness and hydraulic conductivities, the Belvoir Ranch site model will be first calibrated for thickness and hydraulic conductivities using long-term water level data and a steady state groundwater flow model. As part of this calibration, four alternative hydrostratigraphic models will be built reflecting uncertainty in fault orientation, extent, and hydraulic conductivities. These models will be calibrated using both FePEST and the new inversion method. After the steady-state calibration, a transient groundwater model will be simulated and both hydraulic conductivity and storativities will be estimated using (1) single- and cross-hole well test data collected over (short) testing durations; (2) transient water level data from the site collected over the monitoring period.

After all hydrostratigraphic models are calibrated, they will be simulated for a set of proposed pumping programs to define (1) the extent and cone of depression in response to pumping; (2) capture zone of each well; (3) parameter uncertainty for each model (uncertainty analysis techniques will be applied to each pumping program). To understand and quantify calibration uncertainty, stochastic (geostatistical) inversion techniques will be developed for the new inversion method as well.

Publications & Presentations:

Fangyu Gao†, Ye Zhang, 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) 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.*

Student Support:

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 2nd year Ph.D. candidate in the Hydrogeology program at the Department of Geology & Geophysics, University of Wyoming. She has successfully completed her Ph.D. Preliminary Exam during the Fall semester of 2016 and is scheduled to take the Ph.D. Qualifying Exam during the upcoming Fall semester, 2017.

Conferences Attended:

AGU 2016; AGU Hydro Days, 2017

References Cited:

[1] Lidstone and Associate (2012) Final Report: Cheyenne Belvoir Ranch Groundwater Level II, prepared for: Wyoming Water Development Commission, Cheyenne, Wyoming.
[2] Hermann, R., M. Pearce, K. Burgess, and A. Priestley (2004) Integrated Aquifer Characterization and Numerical Simulation for Aquifer Recharge and Storage at Marco Lakes, Florida, in *Hydrology: Science and Practice for the 21st Century,* Volume I, p. 276-283, published by the British Hydrological Society.
[3] Black, W., M. Dawoud, R. Hermann, D. Largeau, R. Maliva, and R. Will (2008) Managing a Precious Resource, *Oilfield Review*, Summer 2008, a Schlumberger quarterly publication, page 18-33.
[4] Zhang, Y., (2013)a Reducing Uncertainty in Calibrating Aquifer Flow Model with Multiple Scales of Heterogeneity, *Groundwater*, doi: 10.1111/gwat.1211.
[5] Irsa, J. and Y. Zhang (2012) A New Direct Method of Parameter Estimation for Steady State Flow in Heterogeneous Aquifers with Unknown Boundary Conditions, *Water Resources Research*, 48, W09526,DOI:10.1029/2011WR011756
[6] Zhang, Y. (2013)b Nonlinear Inversion of an Unconfined Aquifer: Simulation of Acid Gas Disposal in Western Wyoming, *AAPG Bulletin,* Vol. 96, No. 4, p. 635-664
[7]PEST (Model-Independent Parameter Estimation and Uncertainty Analysis), http://www.pesthomepage.org/Home.php

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 FY16 Annual Report for the project is given below.

Wyoming Information Transfer

Basic Information

Title:	Wyoming Information Transfer
Project Number:	2015WY90B
Start Date:	3/1/2016
End Date:	2/28/2020
Funding Source:	104B
Congressional District:	1
Research Category:	Not Applicable
Focus Category:	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

FY16 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 FY2017 RFP topics and research priorities. Cheyenne, WY., April 22, 2016.
- Wyoming Water Research Program Meeting. WRP Advisory Committee review and ranking of water research projects. Cheyenne, WY., November 31, 2016.

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 FY16 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 3-4, 2016.
- Wyoming Water Development Commission/Select Water Committee joint workshop. Presentation on the UW Office of Water Programs and Water Research Program. Cheyenne, WY., June 1-2, 2016.
- Wyoming Water Development Commission/Select Water Committee joint meeting/summer tour. Worland, WY., August 24-26, 2016.
- 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 9-11, 2016.
- Wyoming Water Development Commission workshop and project approval meetings. Cheyenne, WY., March 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.

- Legislative Select Water Committee meeting. Final approval of Omnibus Water Bill funding. UW Office of Water Programs and Water Research Program FY2016 projects. Cheyenne, WY., March 1, 2016.

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 (FY16 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. Long Beach, CA., April 26, 2016.
- Weather Modification Association -- Annual Conference, Wyoming Weather Modification program update. Long Beach, CA., April 27-29, 2016.
- WY Weather Modification Technical Advisory Team - Summer 2016 Meeting, Sheridan, WY., August 24, 2016.

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 FY16 list is given below), participates in the discussions, and presents summaries on WRP activities.

- Wyoming Water Forum, Presentation on Water Research Program final project reports. Cheyenne, WY., September 6, 2016.
- Wyoming Water Forum, Presentation on Water Research Program update. Cheyenne, WY., October 11, 2016.
- Wyoming Water Forum, Presentation on Water Research Program update. Cheyenne, WY., November 8, 2016.
- Wyoming Water Forum, Presentation on Water Research Program update. Cheyenne, WY., January 10, 2017.
- Wyoming Water Forum, Presentation on Water Research Program update. Cheyenne, WY., February 11, 2017.

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. FY16 OWP Director WWA activities and an agenda for the 2016 WWA Annual Meeting are given below.

- Wyoming Water Association Board meeting, (Advisor), Saratoga, WY., June 20, 2016.
- Wyoming Water Association Summer Water Tour, (Advisor), Saratoga, WY., June 21, 2016.
- Wyoming Water Association Board meeting (Advisor), Casper, WY., October 25, 2016.
- Co-Sponsor Wyoming Water Association Annual Meeting & Educational Seminar, University of Wyoming Water Research Initiatives. Casper, WY., October 26-28, 2016.
- Wyoming Water Association Board Meeting, Legislative Review, (Advisor), Cheyenne, WY., January 11, 2017.
- Wyoming Water Association Board Meeting, Legislative Review, (Advisor), Cheyenne, WY., January 17, 2017.
- Wyoming Water Association Board Meeting, Legislative Review, (Advisor), Cheyenne, WY., January 25, 2017.
- Wyoming Water Association Board Meeting, Legislative Review, (Advisor), Cheyenne, WY., February 1, 2017.
- Wyoming Water Association, Legislative Review, (Advisor), Cheyenne, WY., February 8, 2017.
- Wyoming Water Association, Legislative Review, (Advisor), Cheyenne, WY., February 15, 2017.

WYOMING WATER ASSOCIATION
Annual Meeting & Education Seminar
Conference Program
Co – Sponsored by the University of Wyoming
Office of Water Programs

Casper, Wyoming

October 26th and October 28th, 2016

"***Doing More with Less***"

Wednesday, October 26, 2016

9:00 a.m.	**Pre-Program Irrigation District workshop**
12:30 p.m.	**Registration**
1:00 p.m.	**Opening Remarks – Frank Grimes, WWA President and Greg Kerr, UW Office of Water Programs**
1:10 p.m.	**Welcome – Mayor of Casper**
1:15 p.m.	**WWA Advisor Update**
1:20 p.m.	**Kevin Frederick, WY Department of Environmental Quality**
1:40 p.m.	**Scott Talbot, Wyoming Game and Fish Director**
2:00 p.m.	**Harry LaBonde, Wyoming Water Development Director**
2:20 p.m.	**Steve Wolff, Wyoming State Engineer's Office**
2:40 p.m.	**Mark Watson, Oil and Gas Commission**
3:00 p.m.	**Networking Break**
3:30 p.m.	**Restoration Advisory Board for Missile Site 4**
4:10 p.m.	**Bureau of Reclamation Update, Carlie Ronca, BOR**
4:30 p.m.	**Adjourn**
6:30 p.m.	**WWA Board of Director Dinner and Meeting**

<u>Thursday, OCTOBER 27th</u>

<u>Morning Session</u>

8:00 a.m. **River Restoration: Who, Why and What**

Nephi Cole, Governor's Office

Paul Dey, WGFD

Christina Barrineau, WGFD

Jeff Streeter, Trout Unlimited

9:20 a.m. **Q & A**

9:30 a.m. **Networking break**

9:50 a.m. **River Restoration: Where, When and How**

Michael Geenan, Watershed Restoration

Dave Bidelsbach, 5 Smooth Stones Restoration

11:45 a.m. **Adjourn for noon program**

12:00 – 1:00 p.m. Noon Session

<u>Afternoon Session</u>

1:30 p.m. **North Platte River Casper Restoration Background**

Jolene Martinez, City of Casper

Randy Walsh, Stantec

2:45 p.m. **Depart for North Platte River tour**

5:00 p.m. **Adjourn**

6:00 p.m. **Social Hour with Silent Auction and Raffle**

6:30 p.m. **Banquet with Special Recognition of Senator Geis and 2016 scholarship recipients: Jace Berger, Marin Dey, and Catherine Mercer**

Friday, October 28th

8:00 a.m. **Annual Business Meeting – Frank Grimes,** WWA President

9:00 a.m. **Networking break**

9:30 a.m. **Greg Kerr, UW Office of Water Programs**

10:00 a.m. **"Quantifying Return Flow: Coupling water balance and hydrogeophysics approaches." -** Ginger Paige, UW - Ecosystem Science & Management

10:30 a.m. **"High-resolution modelling of precipitation and snowpack in the Wyoming Headwaters region: how model data can be better than observations, and how they can be a guide for what to expect in a few decades" -** Bart Geerts, UW – Atmospheric Science

11:00 a.m. **Closing discussions/Certificates**

11:30 a.m. **Adjourn**

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 FY16 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. San Francisco, CA., December 12-16, 2016.
- Wyoming State Legislature – Senate Agriculture Committee. Wyoming Water Development Commission (Advisor), Omnibus Water Plan/WRP FY2017 Proposals. State Legislature Bld., Cheyenne, WY., January 17, 2017.
- Wyoming State Legislature – House Agriculture Committee. Wyoming Water Development Commission (Advisor), Omnibus Water Plan. State Capital Bld., Cheyenne, WY., February 7, 2017.
- Wyoming State Legislature – Appropriations Committee. Wyoming Water Development Commission (Advisor), Omnibus Water Plan/WRP FY2017 Proposals. State Legislature Bld., Cheyenne, WY., February 9, 2017.

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.

FY16 (and FY15 not reported last year) Presentations for **Project 2012WY81B**: "Multi-Frequency Radar And Precipitation Probe Analysis Of The Impact Of Glaciogenic Cloud Seeding On Snow", Bart Geerts, Atmospheric Science, UW.

- 47th Annual Meeting of the Weather Modification Association, in Fargo ND, 22-24 April 2015. Bart Geerts presented the final ASCII overview (based on Pokharel et al. 2015b), Binod Pokharel presented a case study (3 March 2012), and Xia Chu presented a paper based on Chu et al. (2015).
- 48th Annual Meeting of the Weather Modification Association, in Long Beach, CA, 26-28 April 2016. Bart Geerts presented an overview of the 2017 SNOWIE project.
- Bart Geerts presented ASCII research update at the bi-annual WWMPP Technical Advisory Team meetings every year from 2012 to 2016 (usually in Pinedale in July, and in Cheyenne in January). Bart Geerts also presented at the November "ground schools" for the WWMPP.
- Bart Geerts also presented seminars on cloud seeding to the UW Dept of Renewable Resources (2013/4/08) and to the UW Dept of Chemical Engineering (2016/4/11).

FY16 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.

- 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)

FY16 Presentations for **Project 2015WY89B**: "Quantifying Return Flow in the Upper Wind River Basin", Ginger Paige and Scott Miller, Ecosystem Science and Management; and Andrew Parsekian, Dept. of Geology and Geophysics, UW.

- 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)
- Parsekian A.D., Paige, G.B., Miller S.N., Gordon B.L., Claes, N. 2015. Return flow: untangling the water budget on flood-irrigated fields. 2015 Water Interest Group

Meeting, Oct. 13, 2015, Laramie, WY. (invited presentation)

- Gordon, B.L., Miller, S.N., Paige, G.B, Claes, N., Parsekian, A., Beverly, D. 2015. A Comparison of Methods for Calculating Evapotranspiration in a Semi-Arid Agricultural System, 2015 AGU Fall Meeting, December 14-18, 2015, San Francisco, CA. (poster)
- 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)
- Gordon, B.L., Miller, S.N., Paige, G.B, Claes, N., Parsekian, A., Beverly, D. 2015. Calculating Return Flows and Consumptive Use in a Semi-Arid Agricultural System, 2015 Water Interest Group Meeting, Oct. 13. 2015, Laramie, WY. (poster)
- Gordon, B.L., Paige, G.B, Miller, S.N. (2014), East Fork return flow study, Wyoming Game and Fish Department, Aquatic Habitat Managers. Dubois, WY.
- Claes, N., Paige, G.B, Parsekian, A. D., Miller, S. N., Gordon, B. L., 2015. Characterization of flood irrigation: merging hydrology and geophysics. WyCEHG Water Interest Group and Wyoming Round-Up, 2015, 14th October, Laramie, WY. (poster)
- 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.

FY16 Presentation for **Project 2016WY91B**: "Groundwater Modeling of the Casper Aquifer, Belvoir Ranch, Cheyenne", Ye Zhang, Geology & Geophysics, UW.

- 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

OWP Web Site

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	6	0	0	0	6
Masters	4	0	0	0	4
Ph.D.	5	0	0	0	5
Post-Doc.	1	0	0	0	1
Total	16	0	0	0	16

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, Mar 2014 – Feb 2017. 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.

Publications from Prior Years

1. 2012WY81B ("Multi-frequency Radar and Precipitation Probe Analysis of the Impact of Glaciogenic Cloud Seeding on Snow") - Articles in Refereed Scientific Journals - Aikins, J., K. Friedrich, B. Geerts and B. Pokharel, 2016: Role of a Low-Level Jet and Turbulence on Winter Orographic Snowfall. Mon. Wea. Rev., 144, 3277–3300.
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