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

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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water in Wyoming and the intermountain west and accounts for approximately ninety percent of the total amount of water withdrawn from streams and aquifers.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 used 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 used 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 were 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 were 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.

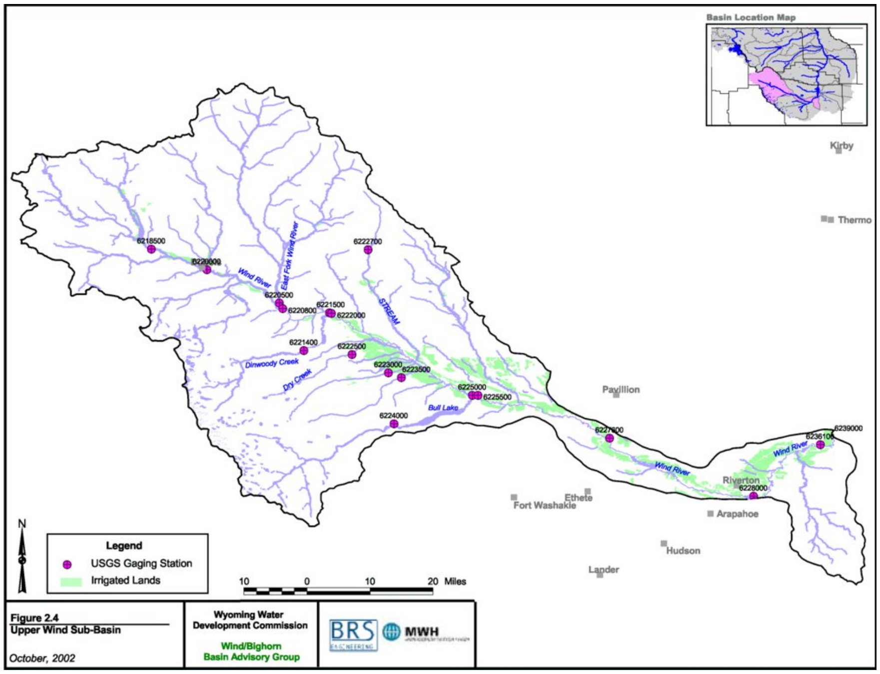


Figure 1. Location of the East Fork in the Upper Wind River Sub-Basin (courtesy: Wyoming Water Development Office *http://waterplan.state.wy.us/plan/bighorn/*)

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

Surface NMR (Nuclear Magnetic Resonance) was used to measure water content in the subsurface. Measurements were 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 borehole NMR measurements were used to measure changes in soil moisture in the subsurface during the intensive infiltration experiments.

Evapotranspiration:
A Large Aperture Scintillometer (which measures sensible heat flux) coupled with a meteorological station were installed to measure climatic conditions and evapotranspiration on one of the irrigated fields (Field 1; Figure 2).

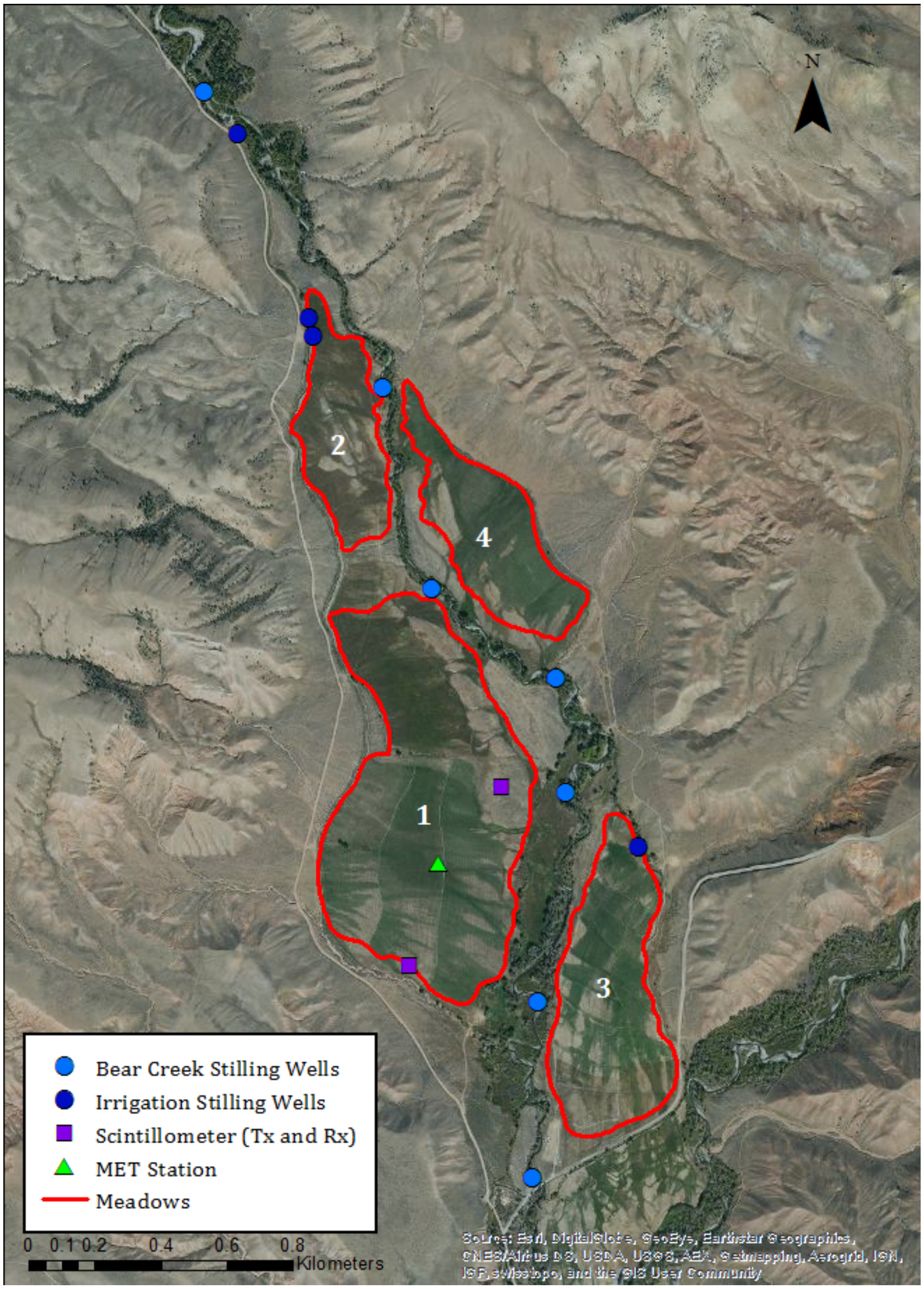


Figure 2. Location of installed instrumentation relative to irrigated meadows and stream.

Reach Scale Water Balance:

The reach scale water balance for Bear Creek was 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 downstream gage.

Water Quality:
Water quality was 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 saw no significant changes in EC or water quality over the course of the study.*

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, 2016 and 2017 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 water level in the phreatic zone between the fields and the stream. These boreholes were fitted with piezometers and a pressure transducer is used to measure any changes in the phreatic zone.

Instrumentation:
A large suite of hydrologic and hydrogeophysical instrumentation were installed or deployed in the Bear Creek Study area (Table 1) over the 2014, 2015, 2016 and 2017 field seasons. Locations of the permanent instrumentation relative to Bear Creek are shown in Figure 2. Together, these measurements were used to 1) characterize the near subsurface and 2) measure the components of the water balance over the irrigation season.

Installed instrumentation, except for the pressure transducers located in 3 boreholes, was removed in October 2017. The 3 remaining pressure transducers were removed in August 2018.

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 June & Aug '17
Seismic/Ground Penetrating Radar/Electrical Magnetic	Subsurface Structures	Jul- Aug '15 Aug '17

Intensive Field Investigations:
A series of intensive field scale measurements using ERT and borehole NMR during irrigation were used to capture changes in soil moisture and identify subsurface flow paths (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 and map wetting front velocities.

Modeling and parameter identification:
To analyze the results of the intensive field investigations, Hydrus and Hydrus 2D (https://www.pc-progress.com/en/Default.aspx), process-based hydrologic models using Richards' equation were used to 1) test observed behavior in the propagation of wetting fronts under flood irrigation and 2) identify hydrologic parameters that describe the observed flow dynamics in the subsurface.

Results:

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).

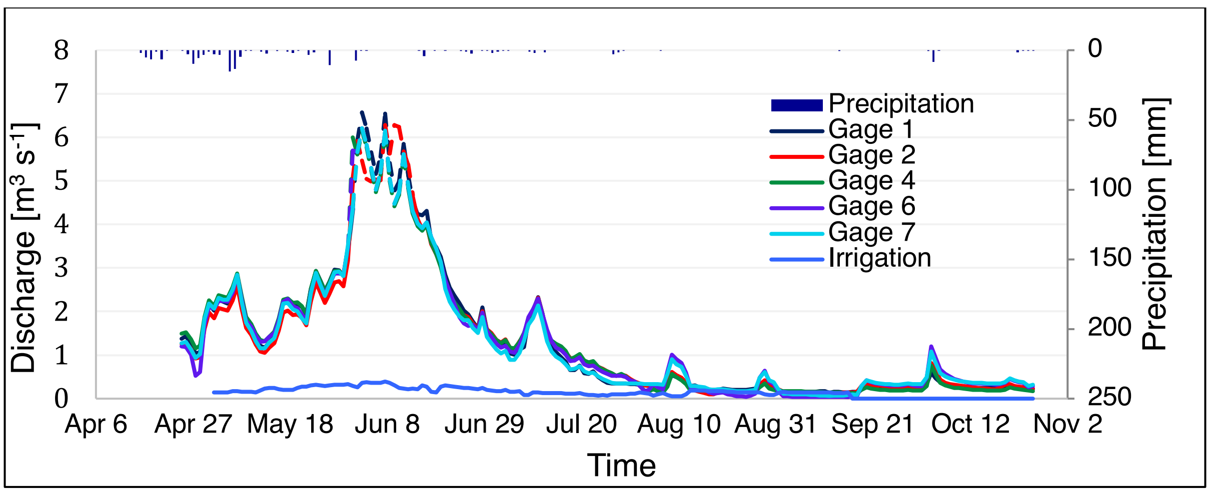


Figure 3. Seasonal hydrographs, precipitation and irrigation from all sites (2015).

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.

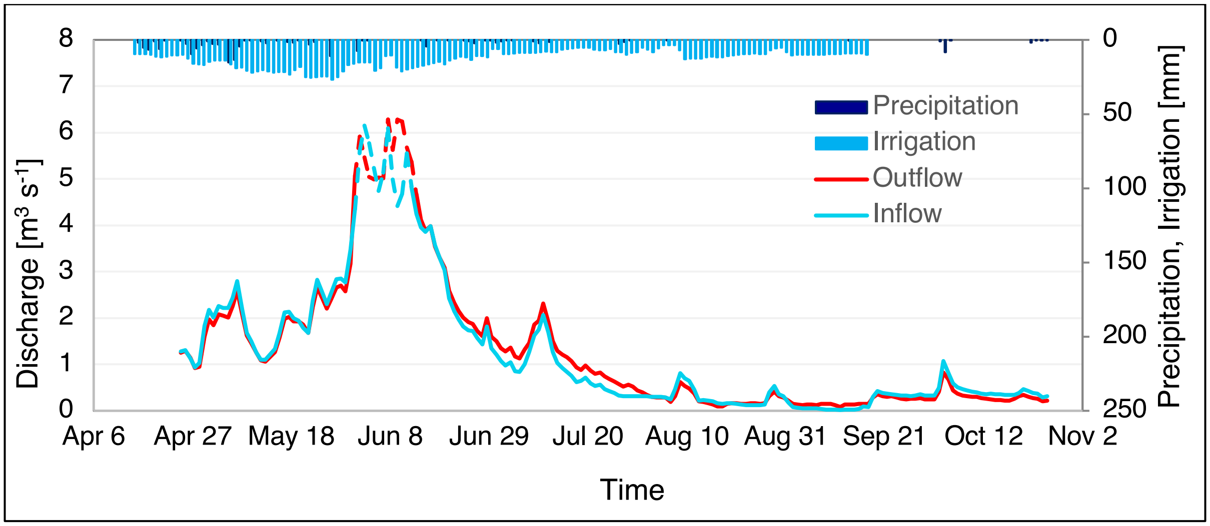


Figure 4. Inflow and outflow hydrographs used to calculate return flow in 2015 (Q_{RT}).

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).

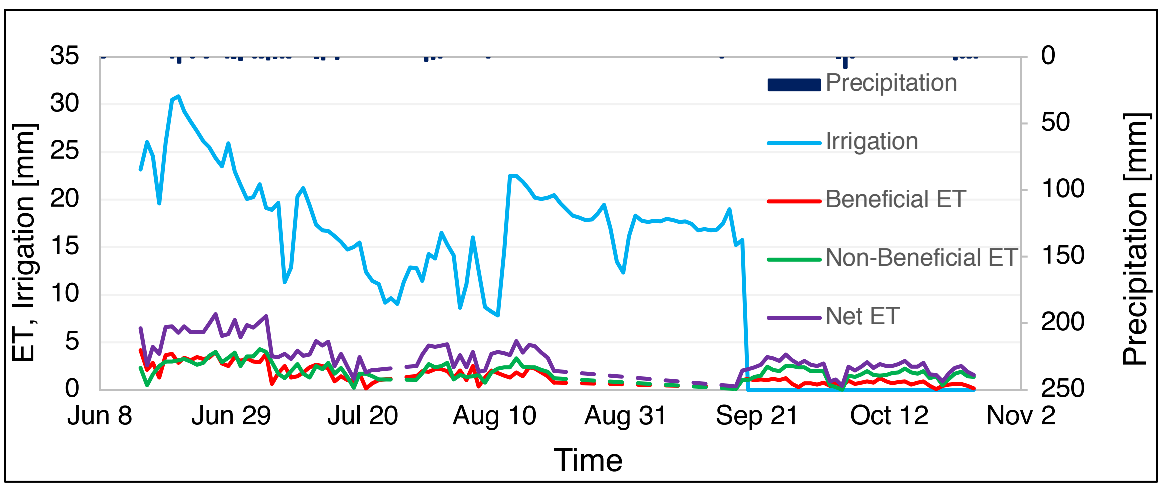


Figure 5. Evapotranspiration for the 2015 irrigation season. Non-beneficial ET is the evapotranspiration for the riparian areas calculated from using Penman-Montheith. Beneficial ET was calculated from the scintillometer.

ET measurements using the scintillometer were continued over the 2016 and 2017 field seasons 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. Similar responses were observed in the 2016 irrigation season. In the 2017 season, there were significant changes in the channel morphology making it difficult to pinpoint the changes in flow throughout the irrigation season. We used some modeling and data approximation techniques to fill in some of the data gaps.

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.

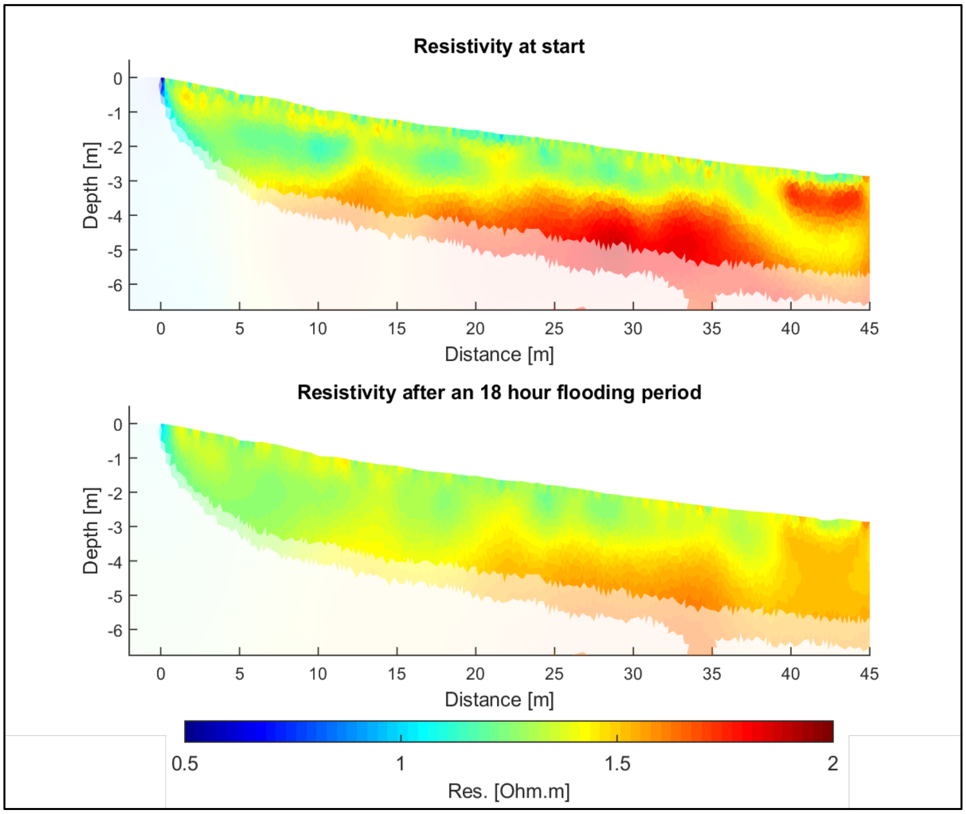
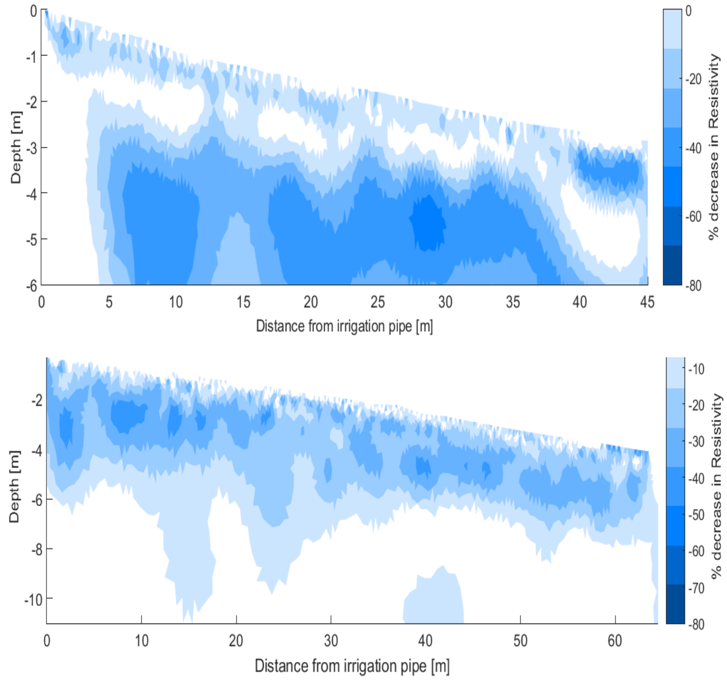


Figure 6. Time Lapse ERT during wetting and drying (before, during and after irrigation applications).

In 2016 & 2017, the intensive field experiments were continued and expanded upon. We completed two wetting and drying studies and were able to map water flow dynamics in the subsurface during wetting and drying phases using time-lapse ERT and borehole NMR measurements (Figures 7 & 8.)



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

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

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

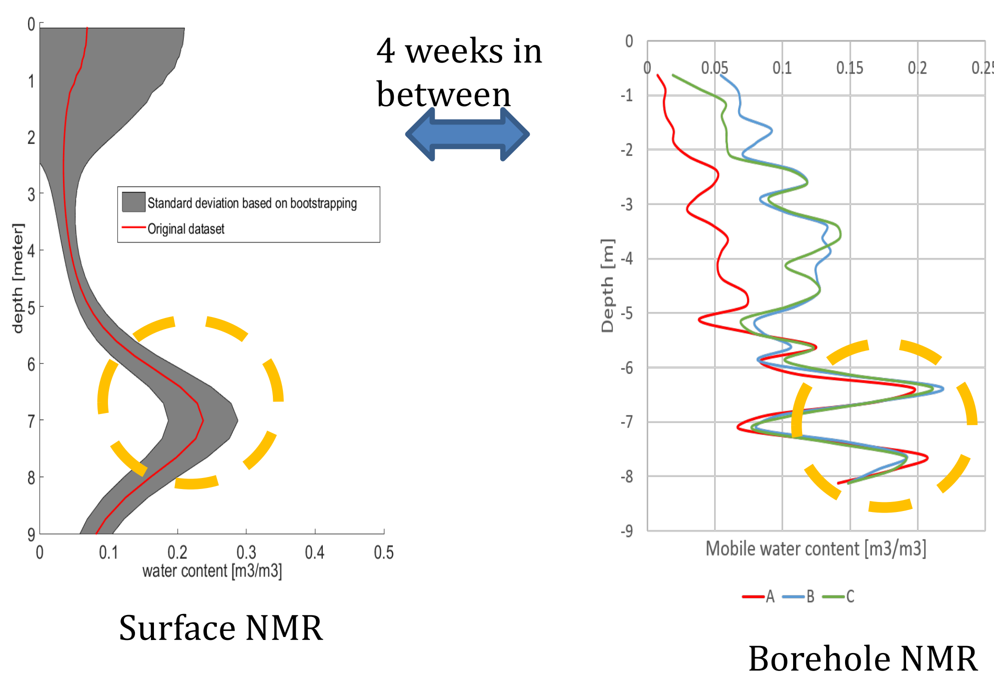


Figure 8. Comparison of results from surface NMR and time- borehole NMR showing water content increasing at the same depth in the subsurface.

Intensive field study results: 2017 irrigation season

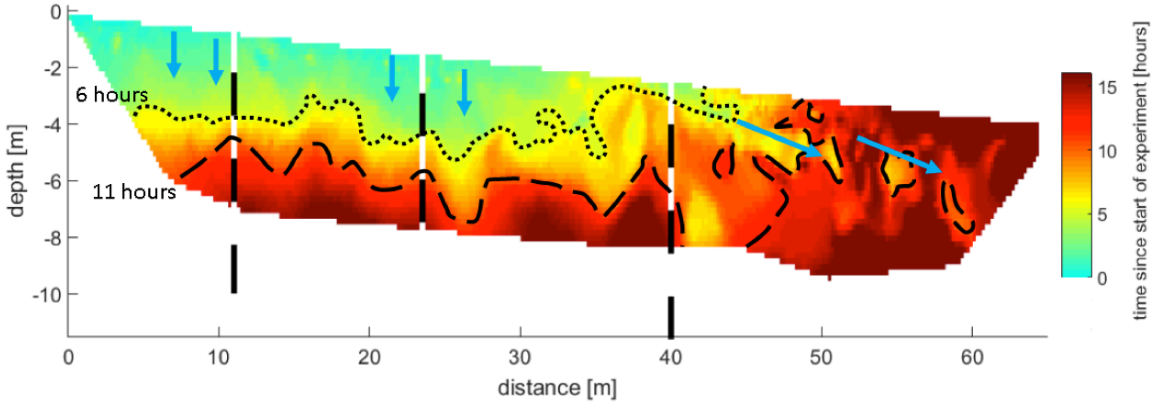


Figure 9. Wetting front velocities and dominant flow paths identified from the time-lapse ERT data.

Key in this project is being able to track the wetting front and flow paths in the subsurface during and following flood irrigation applications. A new method was developed for tracking wetting front in subsurface using time-lapse ERT. The method is based on saturated resistivity and was tested using Hydrus 1D with both synthetic conditions and observations from the field experiments (Figure 10).

The method is able to track the observed movement of the wetting front in the subsurface under intensive water application using time-lapse ERT. The observed wetting fronts were modeled in hydrus 1D using a two layer soil profile.

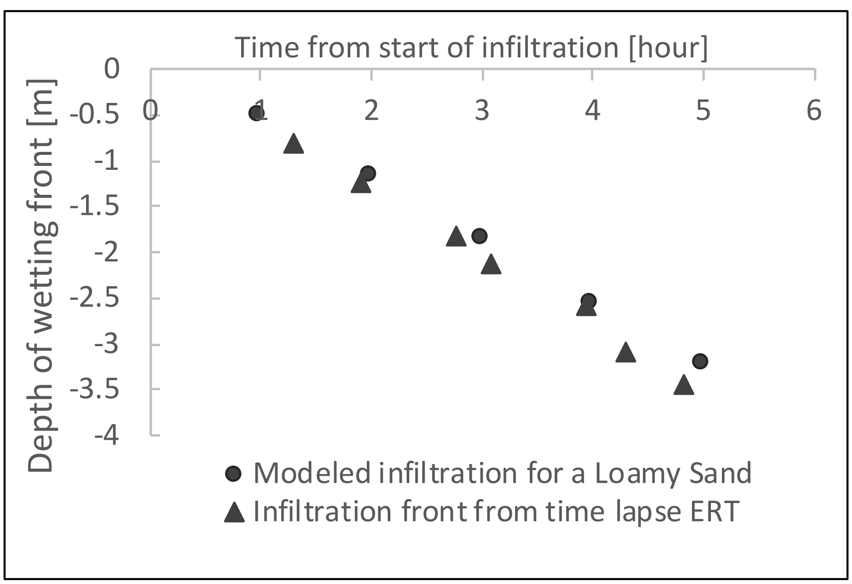


Figure 10. Comparison of modeled and observed wetting front movement in the subsurface under intense irrigation.

Additional field results:

Conductivity: Conductivity (EC) was not found to increase significantly at the study site, and varied between 150 and 280 MS/cm over the course of the irrigation season. However, the conductivity meters installed on the upstream and downstream stations were used track changes in EC over the course of the irrigation seasons.

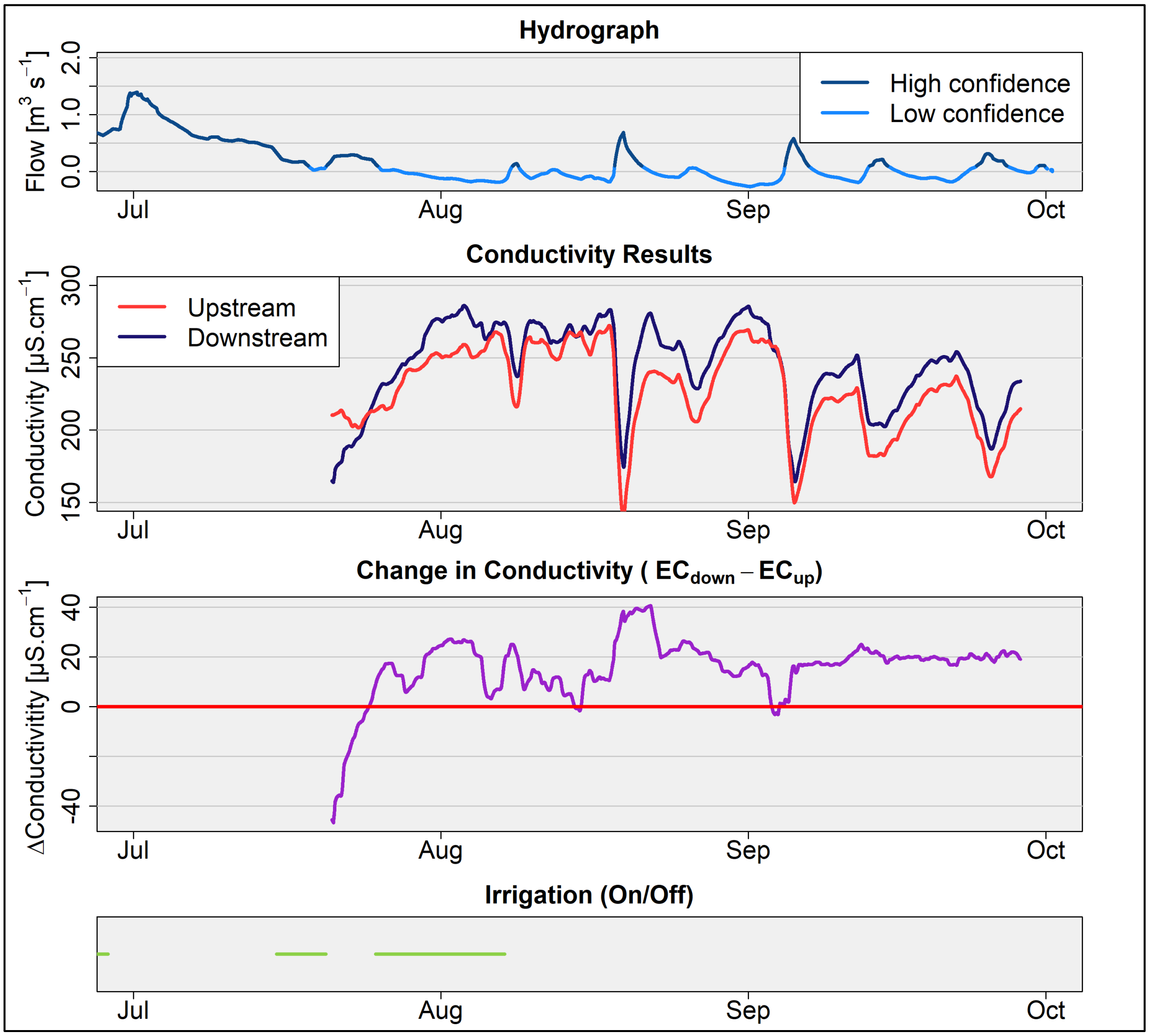


Figure 11: Conductivity analysis using the upstream and downstream conductivity loggers. Return flow signal becomes apparent through the reach analysis.

Comparison with New Fork Study:

This study indicates that between 25% and 38% of applied water (Q_{RT} = 271+/- 32 mm; Q_{IRR} = 867 mm +/-67 mm) returns to Bear Creek. We found that a significant proportion (~28%) of irrigation water in this system went to support riparian areas in the form of ET or storage and roughly 17% of return flow at the site occurred in the month of October, after irrigation had ceased. This is notable because it indicates that the site's quick response to applied water did not preclude late season supplementation of baseflows. Even the higher range of return flow observed at the Bear Creek site (38%), below the amount (50%) assumed by the state (Gordon et al., 201x). Bear Creek return flow provides a lower "bookend" for water managers and policy makers seeking to constrain return flow estimations in a broader range of systems. The other Wyoming study in the New Fork (Wetstein et al., 1989) found an average return flow of 70% with approximately 10% contributing to late season baseflow. Bear Creek return flow results are in line with a Utah study in Bear River (Lecina et al. 2011), which found that 28% of water applied was not consumed by crops. However, direct measures of return flow to the stream system were not made in Lecina et al. (2011) so direct comparisons are difficult.

Summary & Conclusions:

This project successfully applied new methods and techniques to directly quantify return flow from controlled agricultural systems in the Spence/Moriarty Wildlife Habitat Area in the East Fork watershed in the Upper Wind River Sub-Basin in Wyoming. This location was ideal for this study as we were able to work directly with the managers controlling the application and timing of the irrigation water. We used 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 used new methods in hydrogeophysics at the field scale. Geophysics tools were used to map subsurface flow paths, monitor and quantify return flow. The results from the field studies coupled with the reach scale water balance indicate that the majority of the return flow is the result of subsurface lateral flow from the fields.

Results from this study found that return flow in this system was approximately 38%, lower than the 50% assumed by the state water managers and much lower than the ~70% from the New Fork 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.

References:

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

Lecina, S., Neale, C. M. U., Merkley, G. P., & Dos Santos, C. a C., 2011. Irrigation evaluation based on performance analysis and water accounting at the Bear River Irrigation Project (U.S.A.). *Agricultural Water Management*, *98*(9), 1349–1363. http://doi.org/10.1016/j.agwat.2011.04.001

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).

Publications:

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

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

Claes, N. G.B. Paige, A. Parsekian. 201x. Uniform and lateral preferential flow under flood irrigation at field scale. Submitted to Hydrological Processes. (*in revision*)

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

Refereed Publications in preparation:

*Claes, N., G.B. Paige, A. Parsekian. 201x. Parameterization of a hydrological model with geophysical data to determine unsaturated flow paths in the subsurface. To be submitted to Vadose Zone Journal.

*Claes, N., G.B. Paige, A. Parsekian, B. Gordon, S.N. Miller 201x. Flood irrigation generated subsurface flows in a local water balance. To be submitted to Vadose Zone Journal.

*Gordon, B.L., S.N. Miller, G.B. Paige, N. Claes, A. Parsekian, D. Beverly. 201x. *A scintillometer-based evaluation of evapotranspiration in a semi-arid agricultural system*

Presentations:
*Cook, J.N. E.W. Kempema, B.L. Gordon, N. Claes, S.N. Miller, G.B. Paige. 2018. Return Flows: Quantifying water availability. Flow 2018: Managing Rivers, Reservoirs and Lakes in the Face of Drought. April 24-26, 2018. Fort Collins, CO. (poster)

*Claes, N. G.B. Paige, A. Parsekian. 2018. Estimation of wetting front movement at field scale. Annual Symposium on the Application of Geophysics to Engineering and Environmental Problems (SAGEEP). New Orleans, LA. March 28th, 2018 (oral presentation).

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

Paige, G.B. 2017. WyCEHG: Building capacity in hydrology and geophysics in Wyoming. Wyoming Water Association Annual Meeting, Sheridan, WY. October 27, 2017. (invited)

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

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., S.N. Miller, A.D., Parsekian, B.L Gordon, N. Claes. 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)

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)

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.

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.

Graduate Students:
Directly Funded:
Neils Claes, PhD. Program in Hydrology, University of Wyoming.
Started January 2015 – Defending October 2018.

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)