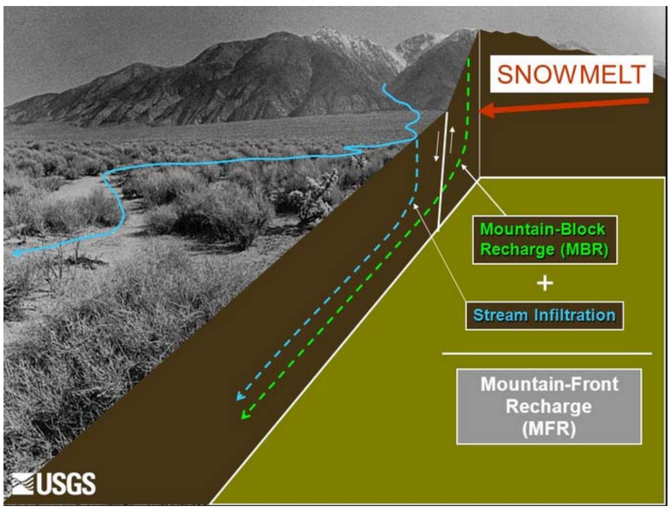
Subsurface Hydrology in a Mountain Watershed

Introduction

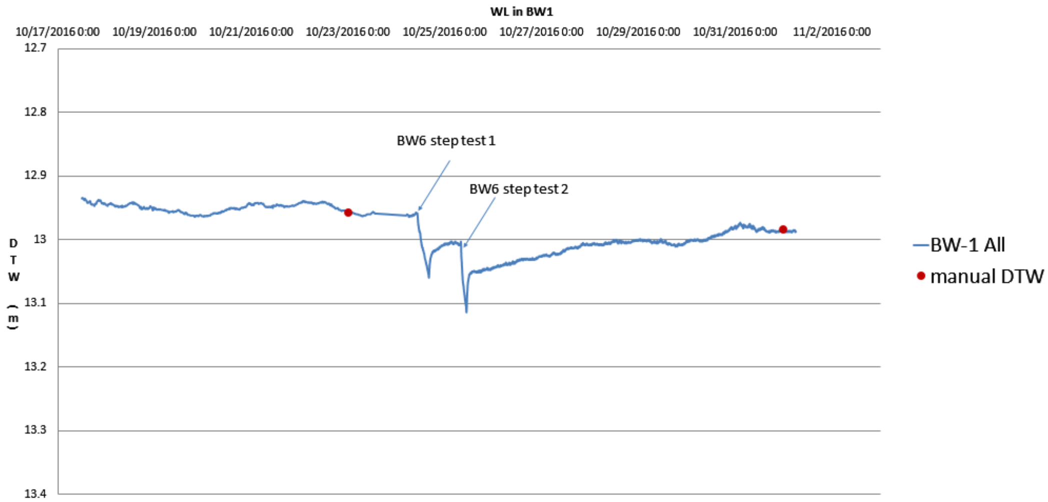
In Wyoming, approximately 60 percent of precipitation falls in the mountains compared to the low lands. This precipitation is partitioned into evapotranspiration, overland flow, and infiltration into the subsurface. Subsurface flow in mountains, an important component of precipitation partitioning, remains largely a mystery. The University of Wyoming *Blair Wallis* Fractured Rock Research Well Field, which lies near the peak of the Laramie Range in southeastern Wyoming, will yield new knowledge into subsurface flow in a mountain watershed in a semi-arid region with snowmelt driven hydrology. The research carried out at Blair Wallis integrates soil and aquifer characterization with borehole and geophysical measurements to understand and quantify subsurface infiltration and flow in this mountain watershed. Because mountain runoff, through both surface and subsurface pathways (see schematics from USGS; Williams, et. al, 2004), recharges basin aquifers that supply the majority of freshwater in the region, we have also established two research well fields (*Belvoir Ranch* and *Government Gulch*) in a basin aquifer that forms outcrop along the eastern and western mountain fronts downstream from Blair Wallis. Though groundwater in this aquifer is primarily sourced from the Laramie Range, location, timing, pathway, and magnitude of this recharge remain poorly known. Research into subsurface hydrology, from Blair Wallis in Laramie Range to mountain front aquifer, will contribute to our understanding of MFR and MBR in a headwater region experiencing climate change and precipitation shifts. Our study will also provide data and models to help develop sustainable water management strategies for southeastern Wyoming.

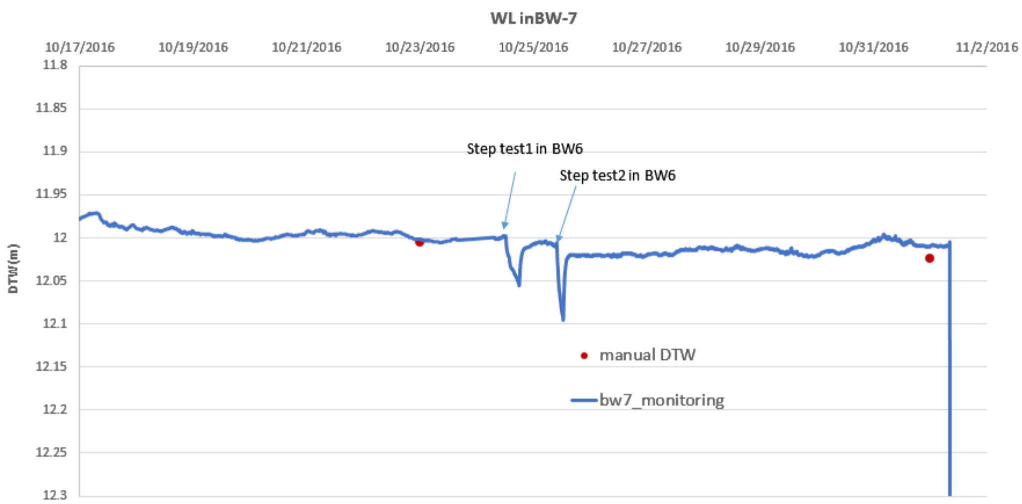


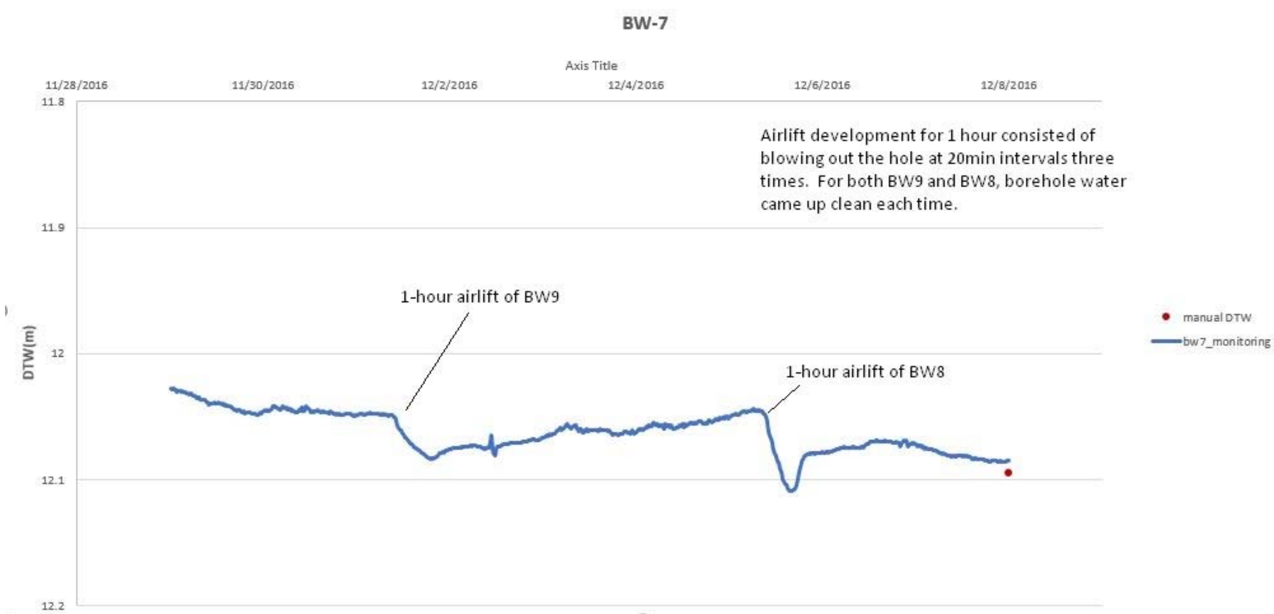
Blair Wallis Fractured Rock Research Well Field

In Fall, 2015, a series of single- and cross-hole hydraulic tests was carried out aiming to estimate aquifer bulk parameters at the wellbore locations (BW1 to BW5). Results are reported in this link: http://geofaculty.uwyo.edu/yzhang/files/Summary_HydraulicTests.pdf Overall, the fractured granite at Blair is capable of yielding significant quantities of freshwater, suggesting an important resource. The aquifer appears strongly heterogeneous, with the slug- and pumping-test derived horizontal hydraulic conductivity (K_H) ranging over 3 orders of magnitude (10^{-4}~10^{-6} cm/s).

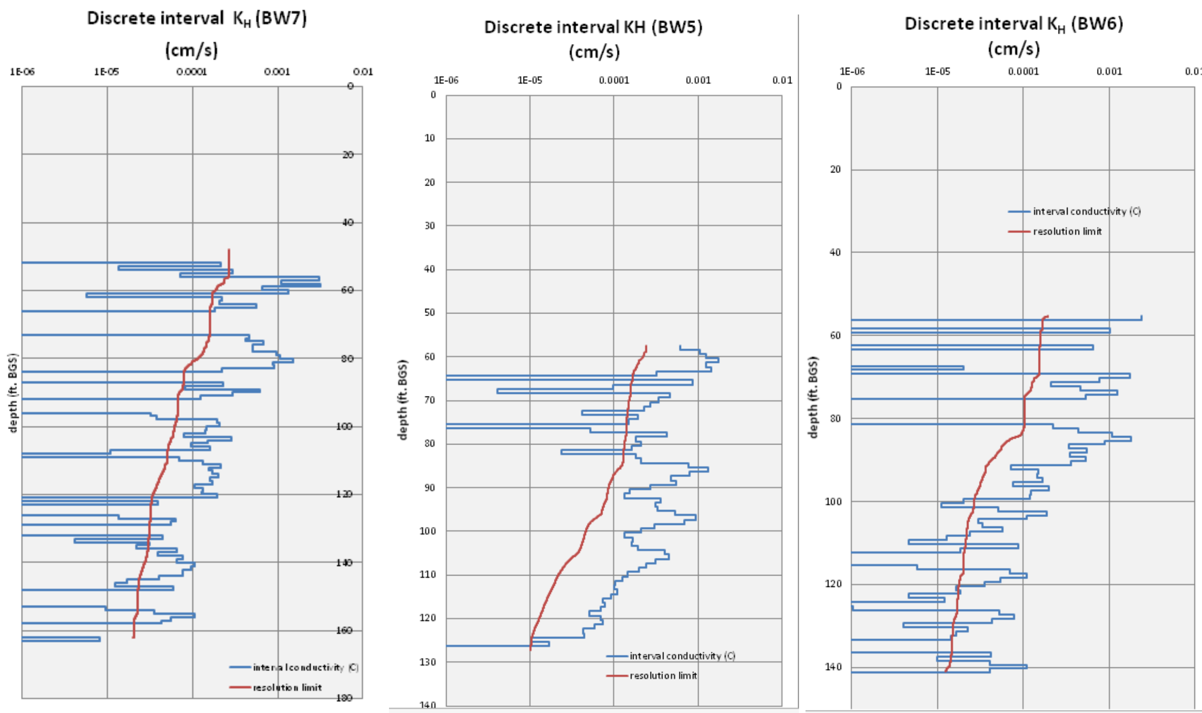
During Fall, 2016, new drilling and testing have identified **cross-hole hydraulic communications** during step testing of BW6 (10/24/2016—10/25/2016; see below hydrographs of BW1 and BW7). And, also during the drilling and airlift development of BW9 and BW8 (11/20/2016—12/5/2016; see below hydrographs of BW7). With cross-hole data, we can estimate additional aquifer properties such as hydraulic diffusivity and storativity.


WL in BW1
10/17/2016 0:00
10/19/2016 0:00
10/21/2016 0:00
10/23/2016 0:00
10/25/2016 0:00
10/27/2016 0:00
10/29/2016 0:00
10/31/2016 0:00
11/2/2016 0:00
12.7
12.8
12.9
13
13.1
13.2
13.3
13.4
DTW (m)
BW6 step test 1
BW6 step test 2
BW-1 All
manual DTW


WL inBW-7
10/17/2016
10/19/2016
10/21/2016
10/23/2016
10/25/2016
10/27/2016
10/29/2016
10/31/2016
11/2/2016
11.8
11.85
11.9
11.95
12
12.05
12.1
12.15
12.2
12.25
12.3
DTW(m)
Step test1 in BW6
Step test2 in BW6
manual DTW
bw7_monitoring


BW-7
Axis Title
11/28/2016
11/30/2016
12/2/2016
12/4/2016
12/6/2016
12/8/2016
11.8
11.9
12
12.1
12.2
DTW(m)
Airlift development for 1 hour consisted of blowing out the hole at 20min intervals three times. For both BW9 and BW8, borehole water came up clean each time.
1-hour airlift of BW9
1-hour airlift of BW8
manual DTW
bw7_monitoring

Moreover, downhole hydraulic profiling by FLUTe yields additional information of high resolution K_H, which suggests that bedrock fractures are responsible for most of the water yield from the wells tested. K_H of discrete fractures is often 1 to 2 orders of magnitude higher than those derived from slug and pumping tests, suggesting "scale effect" due to the different sampling volumes tested (see below FLUTe profiling results). Importantly, **traditional well tests cannot reveal detailed heterogeneity in the subsurface**, in particular, the location of high-K preferential flow paths. New aquifer characterization technology is needed, combining high resolution K_H imaged at borehole locations with geophysical logging and advanced numerical aquifer inversion techniques.



New Research

New research is being proposed to carry out **hydraulic tomography** (HT), a new technology to characterize aquifer heterogeneity at high resolution and to quantify the estimation uncertainty. To our knowledge, there have only been 2 reported applications of HT to characterize fractured aquifers:

- Mizunami Underground Research Site in central Japan: sedimentary rock overlying granite; Depth of the wells ranges from 100 m to 1300 m (Illman et al., 2009, WRR);
- Plattsburgh in New York: a single horizontal bedding plane fracture in a sandstone formation. Depth of the wells ~12 m (Castagna et al., 2011, WRR).

Neither sites lie in mountain environments where hydrology is dominated by snow and groundwater contribution to the water budget is virtually unknown. Though extensive hydrogeophysical research was carried out at the USGS Mirror Lake fractured rock research site in New Hampshire, there is no longer activity there on aquifer characterization in the last decade or so.

After HT is carried out, our next objective is to integrate aquifer characterization with geophysical measurements to look at the mountain hydrology at larger (i.e., away from the well field) scales to derive water balance estimates useful for water management purposes. See below diagram of the proposed research.

Improved subsurface characterization for integrated water balance modeling at the watershed scale

(1) Interpret steady-state and transient well hydraulic data to characterize multiscale K of the fractured aquifer at the Blair Wallis (BW) fractured rock research site; One idea is to do HT (right) in addition to traditional well tests.

(2) Investigations by the geophysics team: subsurface and/or downhole geophysical properties (seismic, resistivity, NMR, GPR, magnetic, gravity) obtained at the same site at multiple scales;

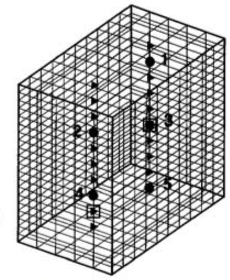
(3) Explore correlations & develop petrophysical relations at multiple scales for (1) loose surficial deposit, (2) granitic matrix, (3) fractures;

(4) Apply the petrophysical relations to obtain watershed-scale K field (away from the wells) at BW where geophysical data provide spatial coverage.

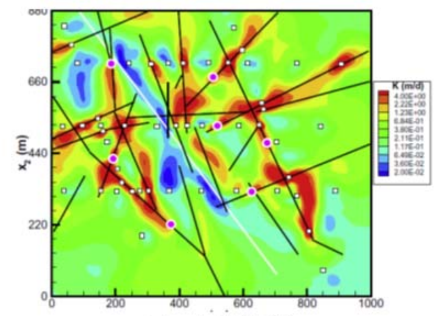
(5) Integrated modeling at the watershed scale in Blair Wallis to quantify sw/gw interaction, including water balance, fluxes, and rate.

(6) Petrophysical relations: site-specific to BW or generally applicable to other granitic aquifers? Test this idea at the NoName watershed in the Snowy Range (with no boreholes) by converting appropriate geophysical properties to K and evaluate if performance of the integrated model will be improved.

3D Hydraulic Tomography (both SS and Transient)



Well schematics:
Circle: Pumping location
Triangle: P monitoring
Box: core sampling



Zha et al. (2014)

References:

Castagna, M., M. W. Becker, and A. Bellin (2011), Joint estimation of transmissivity and storativity in a bedrock fracture, Water Resources Research, 47, W09504, doi:10.1029/2010WR009262.

Illman, W. A., X. Liu, S. Takeuchi, T.-C. J. Yeh, K. Ando, and H. Saegusa (2009), Hydraulic tomography in fractured granite: Mizunami Underground Research site, Japan, Water Resources Research, 45, W01406, doi:10.1029/2007WR006715.

Williams, M., F. Liu, J. Gertson (2004) Mountain block recharge from snowmelt runoff in the Colorado Rocky Mountains, http://hydrologydays.colostate.edu/Abstracts_04/Williams.pdf