Groundwater Well Siting Study

for

Lake Rockport Estates
Rockport, UT

Prepared By:

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1.0 INTRODUCTION AND BACKGROUND

1.1 Introduction

This report presents the results of a geophysical investigation to search out prospective drill targets for groundwater development for Lake Rockport Estates near Rockport, UT (see Figure 1). More specifically, the study searches for subsurface permeability conditions that tend to extend the wellbore reach for more successful production based on historical cases over years of experience. These tools have been used to locate hundreds of wells, the vast majority of which have better yield compared to wells in their respective areas. Nevertheless, it should be understood that the risk of drilling cannot be eliminated, and this study cannot prove or disprove the presence of groundwater at any given location—only drilling can do that. This report discusses the *geophysical investigative approach* followed by a presentation of results and specific target recommendations based on the data.

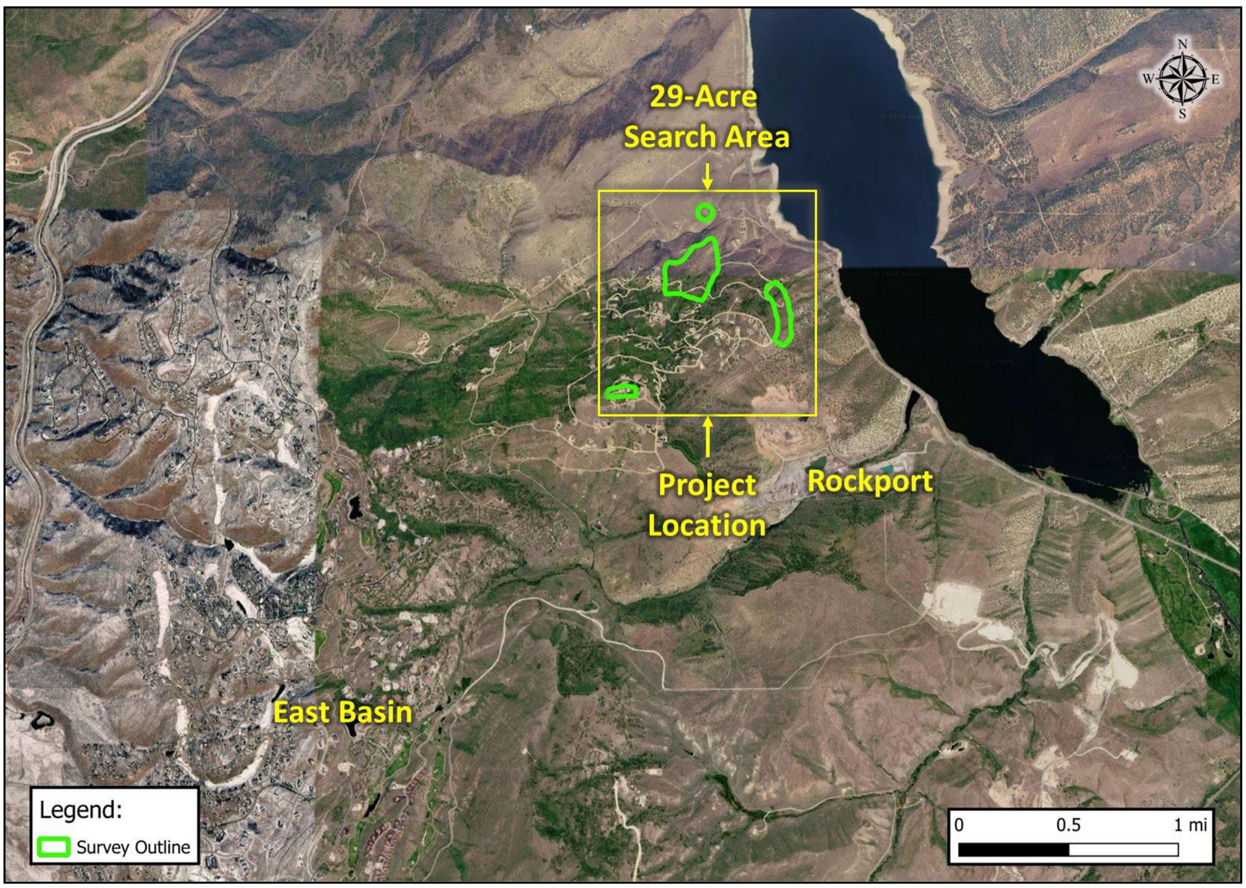


Figure 1: Project Location.

Figure 2 displays a closer view of the study areas with designations A through D and will be here into referred to as such.

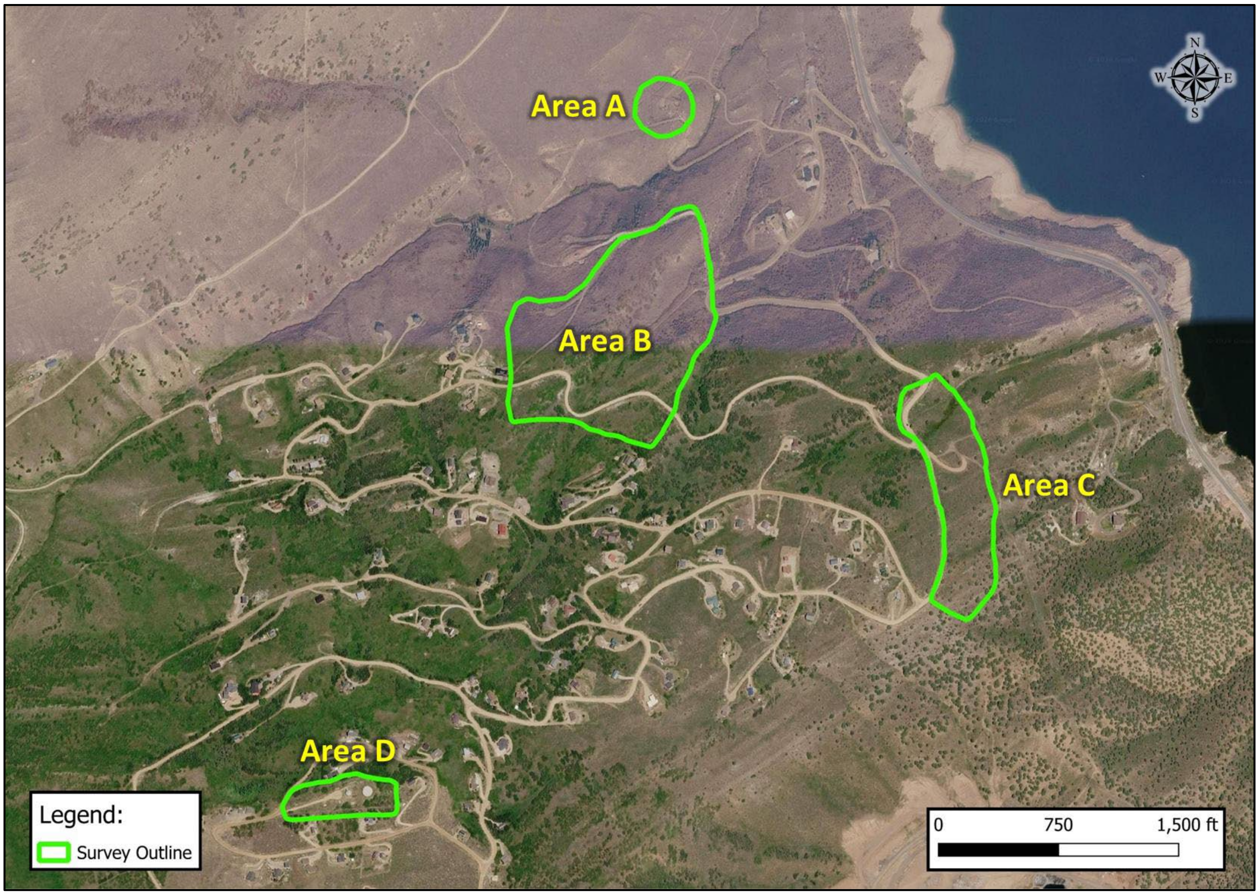
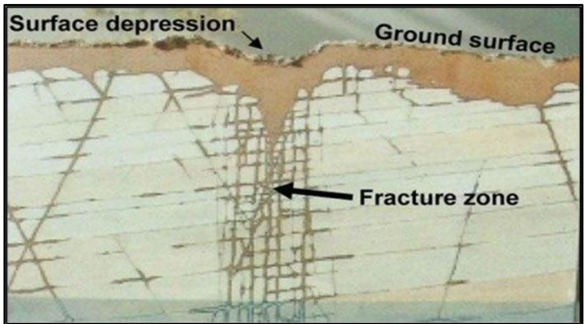


Figure 2: Site Locations.

1.2 Background

In this study, we use innovative geophysical tools and methods to search for natural fracture networks or high-porosity zones in the subsurface that could greatly extend the wellbore reach to support higher than average volumes of water production. It is commonly observed that wells drilled into fractured bedrock formations usually have much greater yields than average. For example, in a 2013 hydrogeologic study comparing over 90 well logs in a large Utah basin, the conclusions state that wells with highest yield were drilled into "*highly fractured"* volcanic rocks, and "*the greatest potential for water movement is where faulting has bisected the rocks at depth*" (Iron Springs Corporation, 2013). In alluvial (valley) drilling, high porosity zones are important to groundwater storage and production. In consolidated bedrock formations, open fracture systems are crucial. Another term for it is fracture networks or high fracture-porosity networks. This is further emphasized in an article published on the PennState Extension website titled "Water Well Location by Fracture Trace Mapping" (Swistock and Sharpe, 2015). The term "Fracture Trace Mapping" refers to detectable lineaments that give clues to subsurface fracture patterns. The following table from the article shows the significant increase in yields recorded in wells across Pennsylvania when fracture detection methods were used before drilling (see Table A). Note that the geophysical tools used in this investigation provide much better clues—even depths of fracture networks—compared to surface lineament mapping.



Rock Type	Avg. Yield (gpm)	Yield from Fractures (gpm)
Crystalline (marble, etc)	1-20	200-500
Sandstone, shale	5-60	100-500
Carbonate (limestone, etc)	5-500	500-3,000
Unconsolidated (gravel, sand)	100-1,000	Not applicable

Table A: Comparison of water yield from typical wells versus fracture-trace wells in various rock types (from Swistock & Sharpe, 2015)

It has been observed, especially in mountainous regions, that aquifers can be very "hit and miss"—more like a "plumbing system" often with deeply-rooted sources in sub-vertical fracture systems, where the model of a "holding basin" does not fit. Precision drilling in such conditions is a must. This investigation uses a unique passive seismic technique to specifically target zones of higher porosity and permeability such as fractured bedrock or unconsolidated gravel zones. The technique is used in conjunction with a radiometric gamma technique tuned for detecting useful patterns and lineaments which may also include evidence where water vapor "venting" can occur. The combination has proven extremely helpful for improved drill target selection in many case studies and counting. These techniques are explained in the next section.

2.0 INVESTIGATIVE APPROACH

2.1 Geophysical Survey Tools for Pinpoint Targeting

Since 2004, Willowstick has specialized in groundwater mapping and has completed over 600 groundwater mapping projects worldwide. Willowstick's seepage tracking tool, for example, has been used extensively for nearly 20 years in mining applications, dams, environmental applications and more with numerous published case studies (Jessop et al., 2018; Park and Jessop, 2018) to name a few, as well as patents (Kofoed et al., 2017; Jessop et al., 2014). For this groundwater well siting study, two of Willowstick's unique tools (geophysical techniques) are deployed to determine specific drill targets—namely, Radiometric Gamma and Micro-seismic Resonance or MSR, a passive seismic technique. The goal is to find targets that appear highly prospective from multiple sources of information, including lineament studies and subsurface seismic profiles. In the case of bedrock aquifers, we search for fracture networks—especially for anomalies that indicate subvertical zones of open fractures having deep roots extending vertically. These often extend a few kilometers downward and sometimes down to the crystalline basement, and they provide significantly for vertical transfer of fluid in earth's crust (Kouznetsov, 2016). A brief description of each geophysical technique is provided below.

2.2 Radiometric Gamma

The Radiometric Gamma system measures aggregate and spectral gamma signals in a rapid and reliable manner, enabling the generation gamma maps covering large areas fairly quickly, making it one of the scouting tools of choice. The signals are analyzed for lineaments and patterns that can reveal much about geologic changes and geologic structure such as faults and dikes, including patterns related to groundwater movement in "plumbing-type" aquifer systems mentioned above. It is nearly always used in conjunction with the MSR system when searching for fracture networks or even permeable gravel zones (when searching in valley alluvial zones) that could greatly increase groundwater yield and reduce costs of drilling.

2.3 Microseismic Resonance (MSR)

The continuous cycle of tidal motion affecting the oceans is common knowledge. Ocean tides are driven by the gravitational tug of the moon and sun. A much lesser-known fact is that the same forces cause tidal movement in the earth's crust which induces continuous microseismic energy (see Kouznetsov, 2016). Earth tides may cause anywhere from 6 to 22 inches of crustal rising and falling motion daily depending on the location. Compared to the earth's 8000-mile diameter, 6 to 22 inches may seem minor; nevertheless, when considering many thousands of feet of rock beneath our feet in constant motion, we can start to appreciate the magnitude of tidal stresses. Stresses that build in the earth's crust from earth tide are accommodated by principal stress-release zones, especially along deep basement faults and subvertical open fracture zones conducive to fluid transport.

The MSR system measures resonance signals induced by microseismic energy in the earth to locate stress relief zones such as fracture networks in bedrock. The technique can also detect layering and porous uncemented gravel zones that may offer ideal targets in alluvial environments. In a way, an MSR "shot" is like a "laser" measurement—highly sensitive to vertically incident waves from the subsurface, apt for pinpointing targets for high-accuracy drilling. Depending on settings, the system can reveal details in shallow or deep zones and has been used to study to depths of 6500 feet (2000 m) and greater in deep applications.

2.4 Work Schedule and Proceedings

A total of 48.5 acres was searched or scouted out by collecting gamma data. The data was used as a guide to detect localized geologic changes and possible lineaments and to guide the MSR seismic lines more effectively. The results are presented in the next section of this report. A total of 7.4 miles of gamma data was collected and used to create the map. MSR data collection took place on 41 survey lines and 48 grid lines. Shot data was processed to 1000 feet depth below ground surface (bgs). Field crews coordinated with one or more geophysicists in the office to complete the full data collection process. Full processing and analysis took place afterwards.

All gamma and MSR measurement data were collected in conjunction with GPS coordinates to correlate the findings. Each MSR measurement station is labeled "L-S" to designate the Line# and Measurement Station#. For example, a label of "3-5" would indicate Line 3, Station 5. With the data acquisition, processing and filtering, all results were compiled into a GIS database for analysis, comparison, and interpretation and to facilitate generation of maps, figures, and depth profiles. All information was used in conjunction to select drill targets.

3.0 SURVEY RESULTS

3.1 Results of Radiometric Gamma Survey

Figures 3-6 show the completed gamma survey results. In the gamma map, the color scale from low to high ranges from green to yellow to orange. The readings are relative and are interpreted by relative comparison—given different background levels and adjustments for each site. The full range in intensity of gamma emissions was from 110 to 260 CPS or gamma events in counts per second. This is a typical range for the mixed alluvium found in the area.

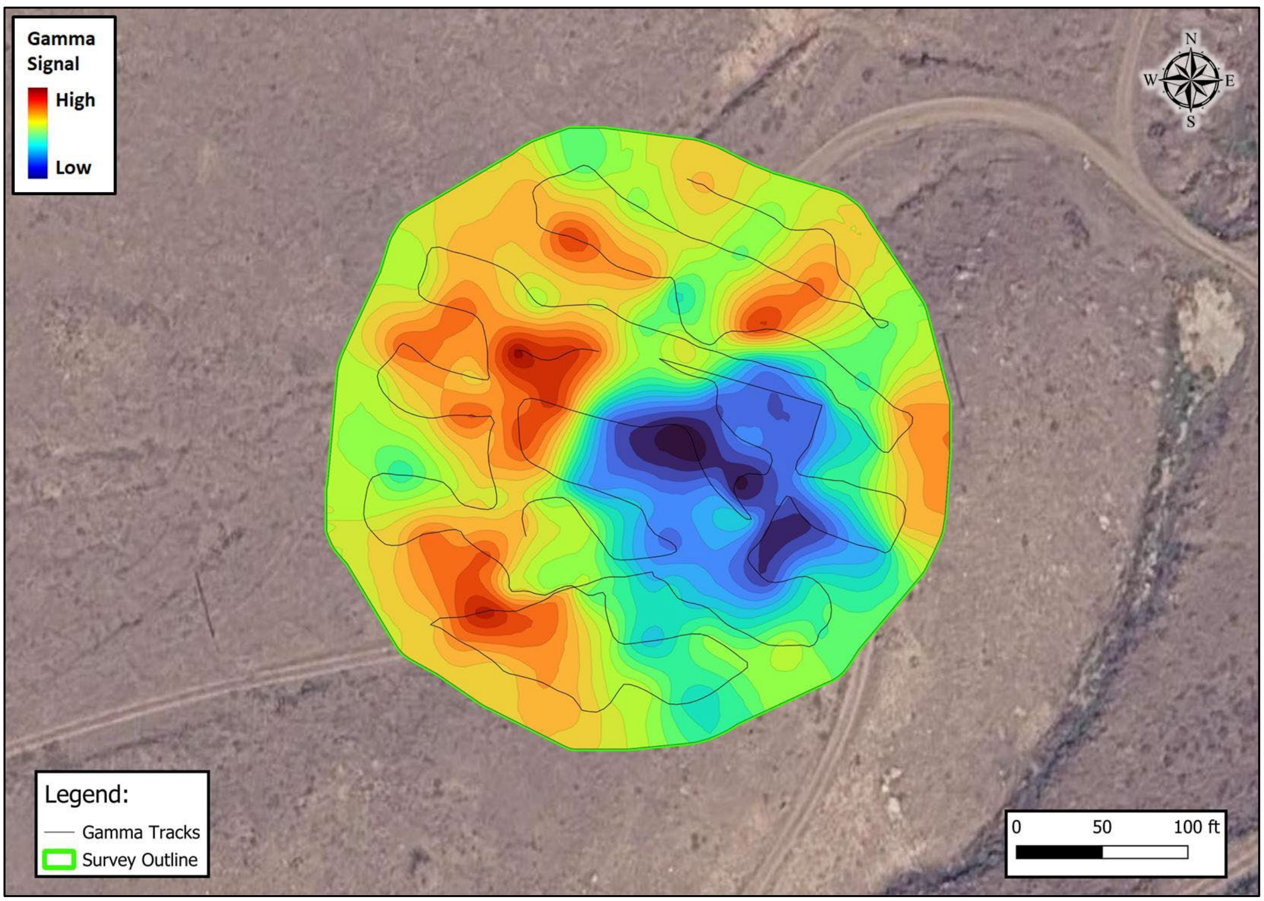


Figure 3: Gamma Results Map Area A.

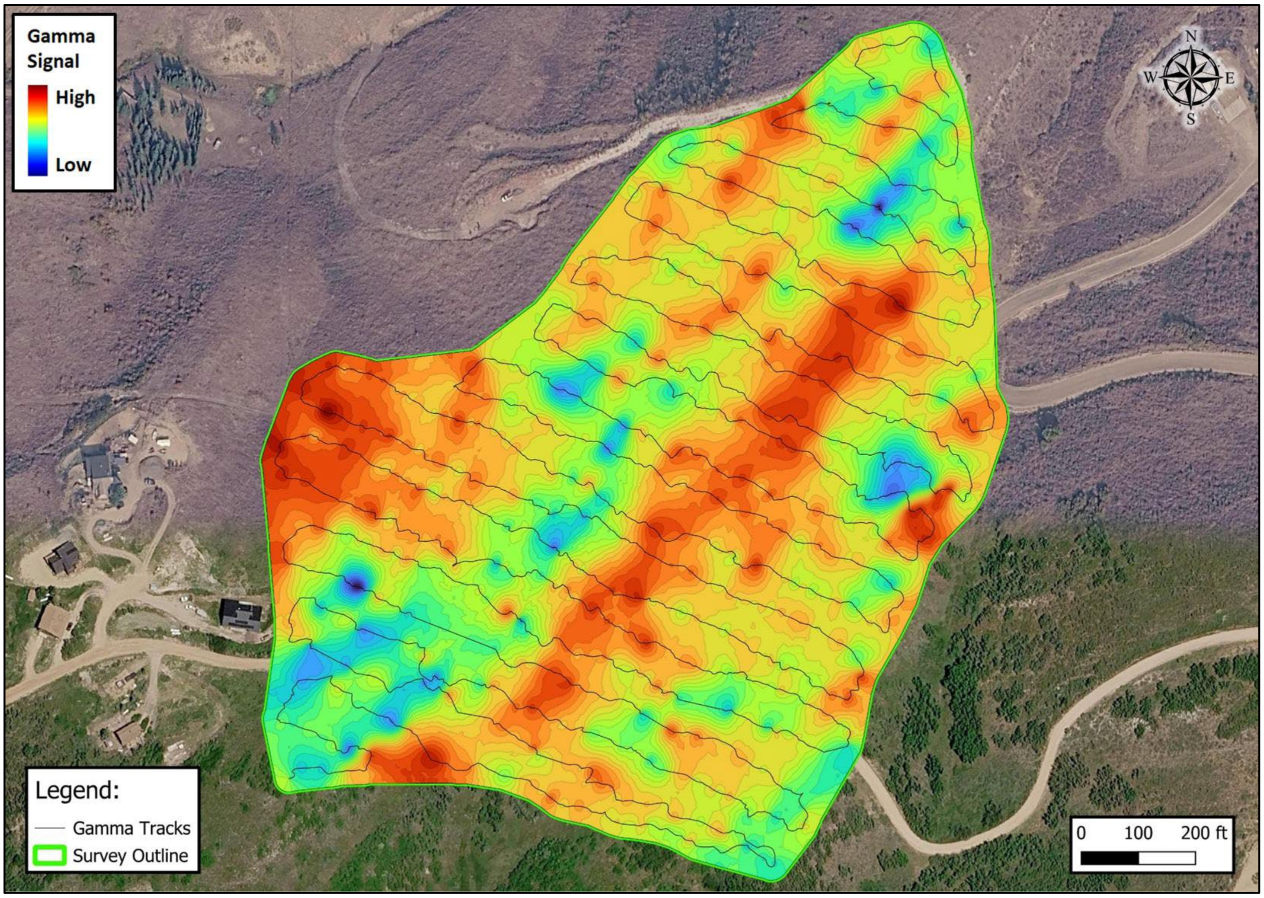


Figure 4: Gamma Results Map Area B.

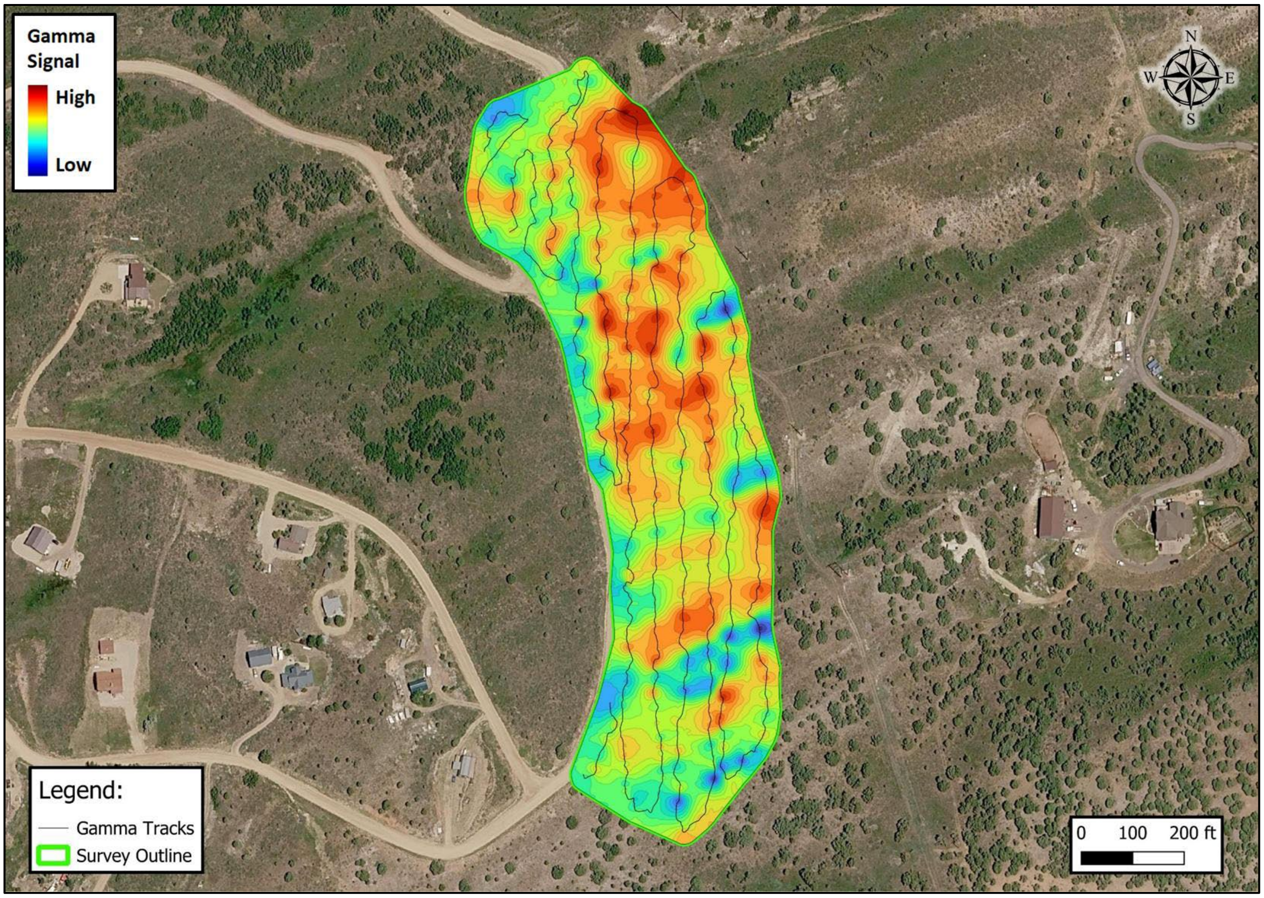


Figure 5: Gamma Results Map Area C.

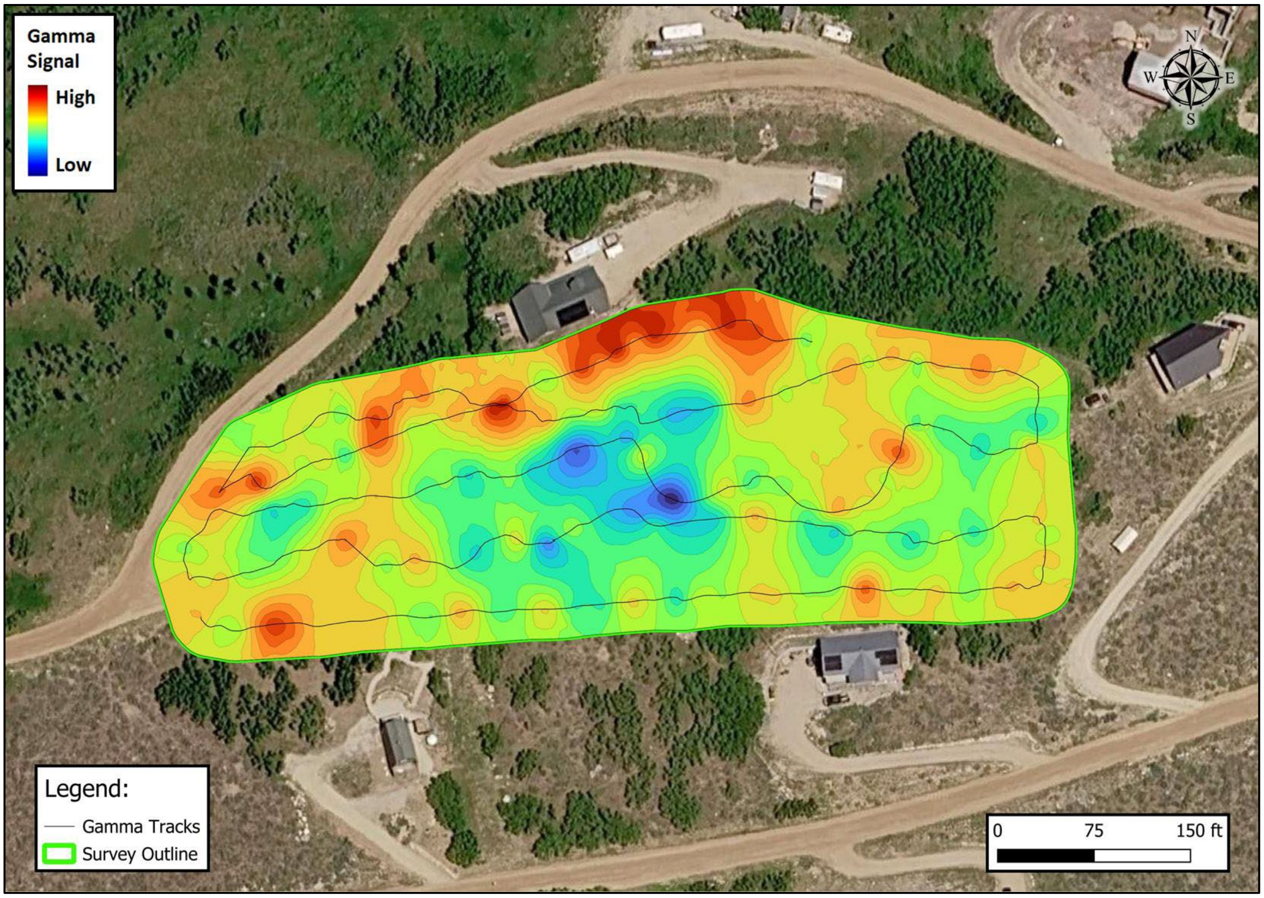


Figure 6: Gamma Results Map Area D.

Gamma patterns provide clues about subsurface structural trends where possible fracture or extensional patterns occur and where MSR can be best applied to locate prospective drill targets. Groundwater distribution can impact the level of gamma emission, particularly in "pockets" and lineaments where deep fissures and/or water-filled fracture zones may exist and where it can facilitate "venting" of water vapor from subsurface fractures up into the atmosphere. A comprehensive study of 43 wells within 3 km of the study area revealed an average well depth of 338 feet and varying levels of production from the producing wells of 2 gpm to 150 gpm. Analysis of this information, especially on nearby wells if any exist, can help to understand depth zones where production tends to occur.

The gamma trends and patterns are sensitive to geologic factors including rock and soil type as well as subsurface structure such as faults and dikes. Even in unconsolidated zones (clay, silt, sand, gravel), the gamma signal can detect lineaments or features influenced by deeper fault or dike structures. These deeper structures tend to affect overlying strata and influence groundwater movement (see Gay, 2012). The gamma "footprint map" does not provide a direct indication of depth, but it does help to focus the MSR seismic work within areas that have higher probability for intercepting groundwater, and the MSR work provides estimates of depth of the more permeable or fractured zones.

Although gamma patterns provide certain indicators that may relate to groundwater extraction potential, it should be understood that the lower readings do not necessarily indicate or prove groundwater—many factors must be considered, and MSR resonance or permeability patterns are often the most important factor. Lineaments and patterns suggesting higher propensity for groundwater in a given area may occur at any gamma level, but the lower trends are usually of top interest unless they are being influenced by some other known factor.

3.2 MSR Seismic Results and Recommended Locations

The MSR data was collected along specific lines, the placement of which was based largely on the gamma interpretation. The goal is to search the subsurface for fracture networks or high porosity zones at depth which correspond also with ideal gamma patterns, and to locate and narrow down prospects for drill targets. All survey MSR measurements were collected on a 5-m (16.4-ft) interval spacing. Once the survey lines were complete areas of particular interest were subsequently gridded. Figures 7-10 show the locations of all 89 MSR lines, each labeled at its *first measurement* (station 1) which is also denoted by a larger circle. It is helpful to keep this in mind while viewing the MSR profile sections and correlating each with its location, orientation, and starting point.

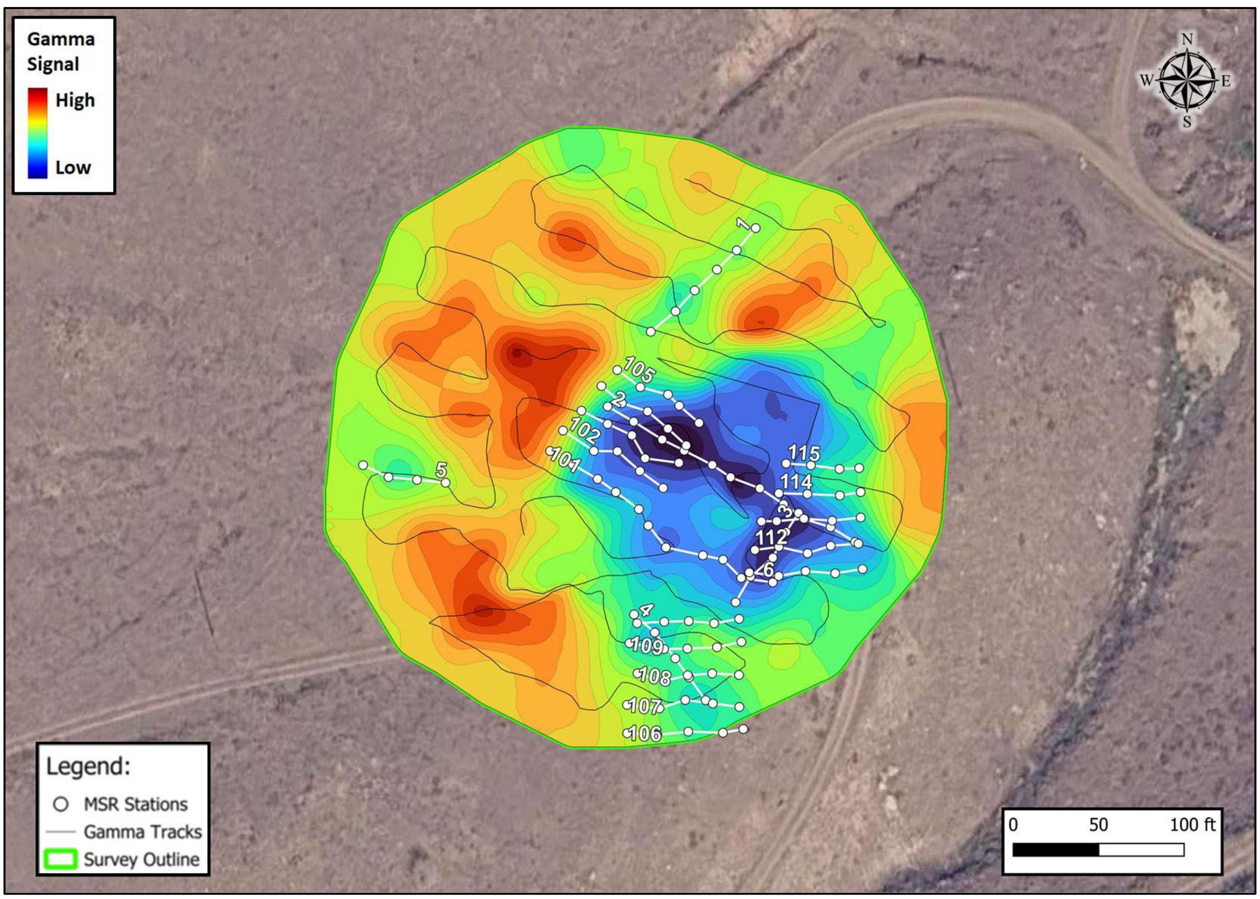


Figure 7: MSR Line Locations Area A.

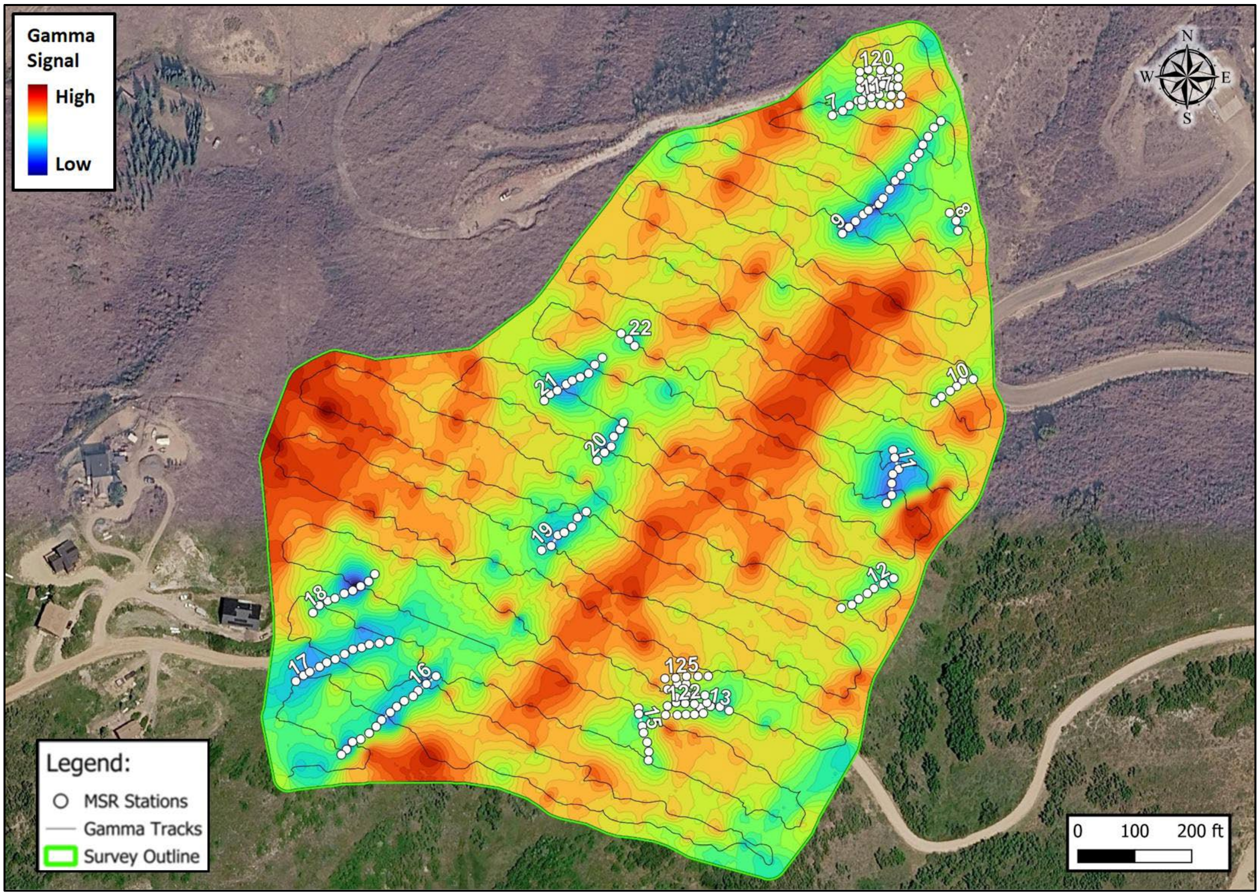


Figure 8: MSR Line Locations Area B.

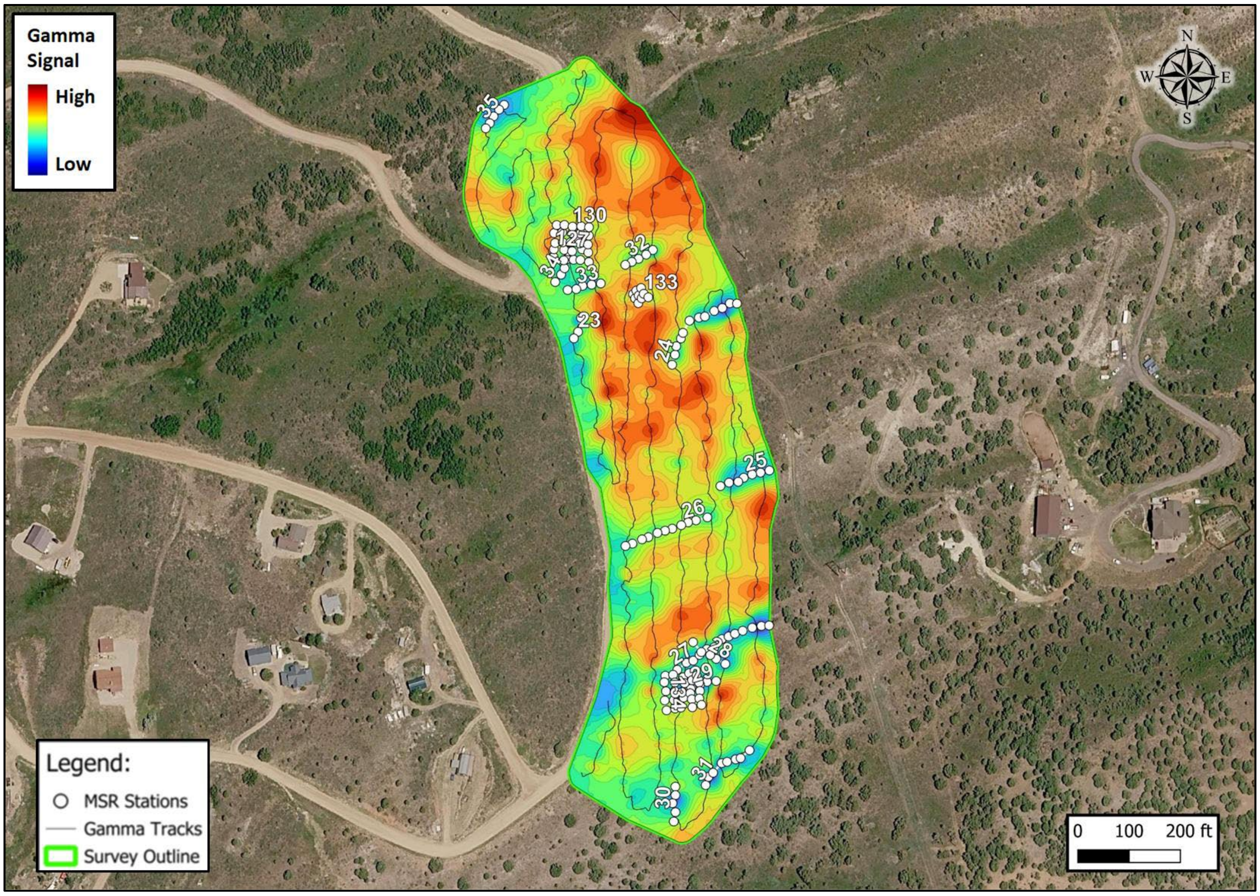


Figure 9: MSR Line Locations Area C.

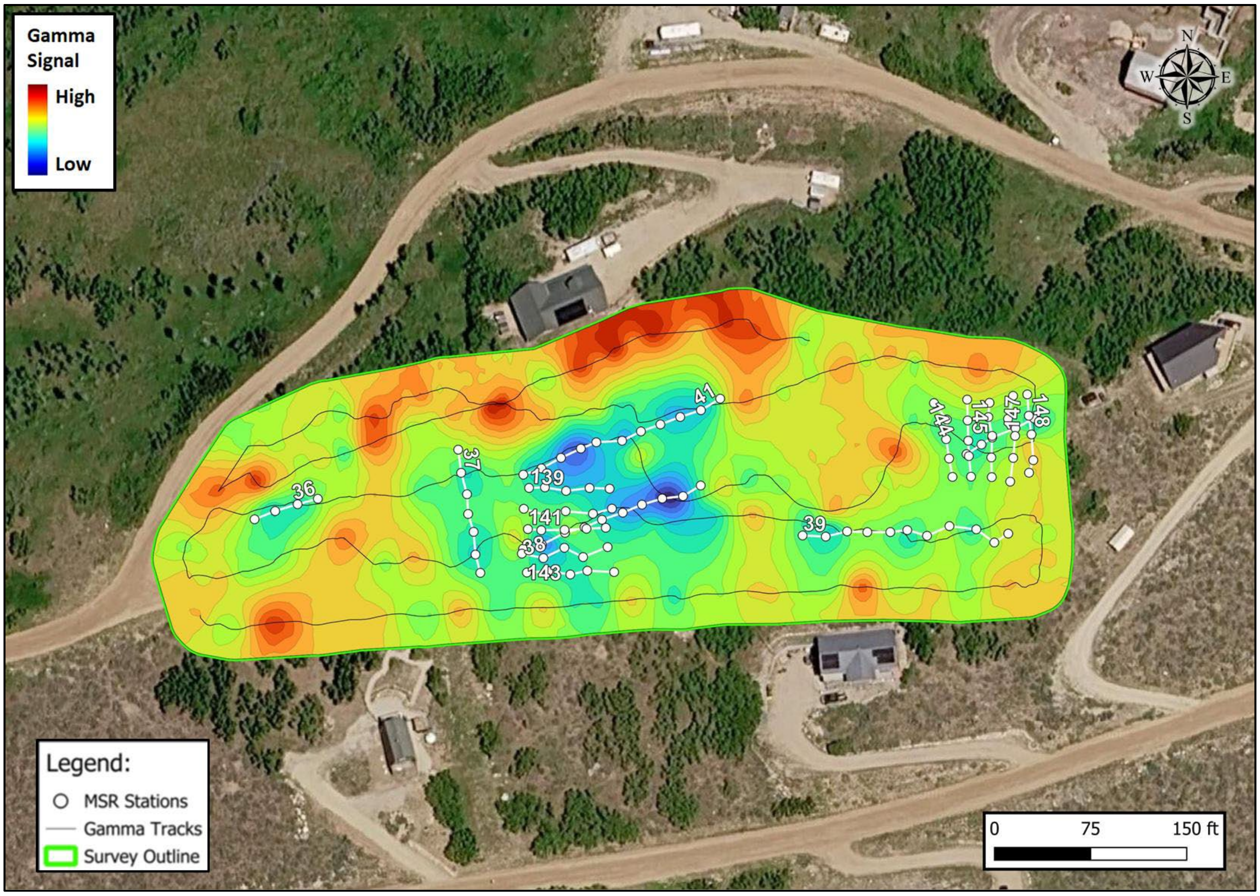


Figure 10: MSR Line Locations Area D.

Note that MSR profile sections use lighter colors to represent low resonance intensity and darker colors to represent higher resonance intensity, as the MSR scale shows. This is an indicator of effective permeability such as open fractures in bedrock or porous gravel zones in unconsolidated alluvium. Keep in mind that the depth shown in MSR sections is an *estimate* based on averages or typical seismic velocities. The estimates can vary depending on unknown conditions, so the depth can only serve as a guide based on past experience.

After analyzing all the survey MSR measurements in conjunction with surrounding gamma patterns, we chose for each area two locations that stood out as the most favorable for prospective drilling, making eight targets total. Extra data was collected around each of these prospects, so there are multiple lines or "angles of view" corroborated and considered in the choices. Figures 11-14 show the two targets in each area, (A1, A2, B1, B2, C1, C2, D1, D2) with subsurface MSR "section" views shown on Lines 112, 4, 7, 122, 29, 34, 40, and 38, respectively. The corresponding MSR lines are shown along with each one's position on the map. In the MSR profile sections, vertical white lines are used to visualize boreholes at the recommended locations. The borehole depths drawn are just for visual purposes (such as, 500 to 900 feet), but the actual depth of drilling will depend on many other factors and especially by what is discovered during the course of drilling. If the air rotary method is used, this usually allows production capability to be estimated while drilling is in progress.

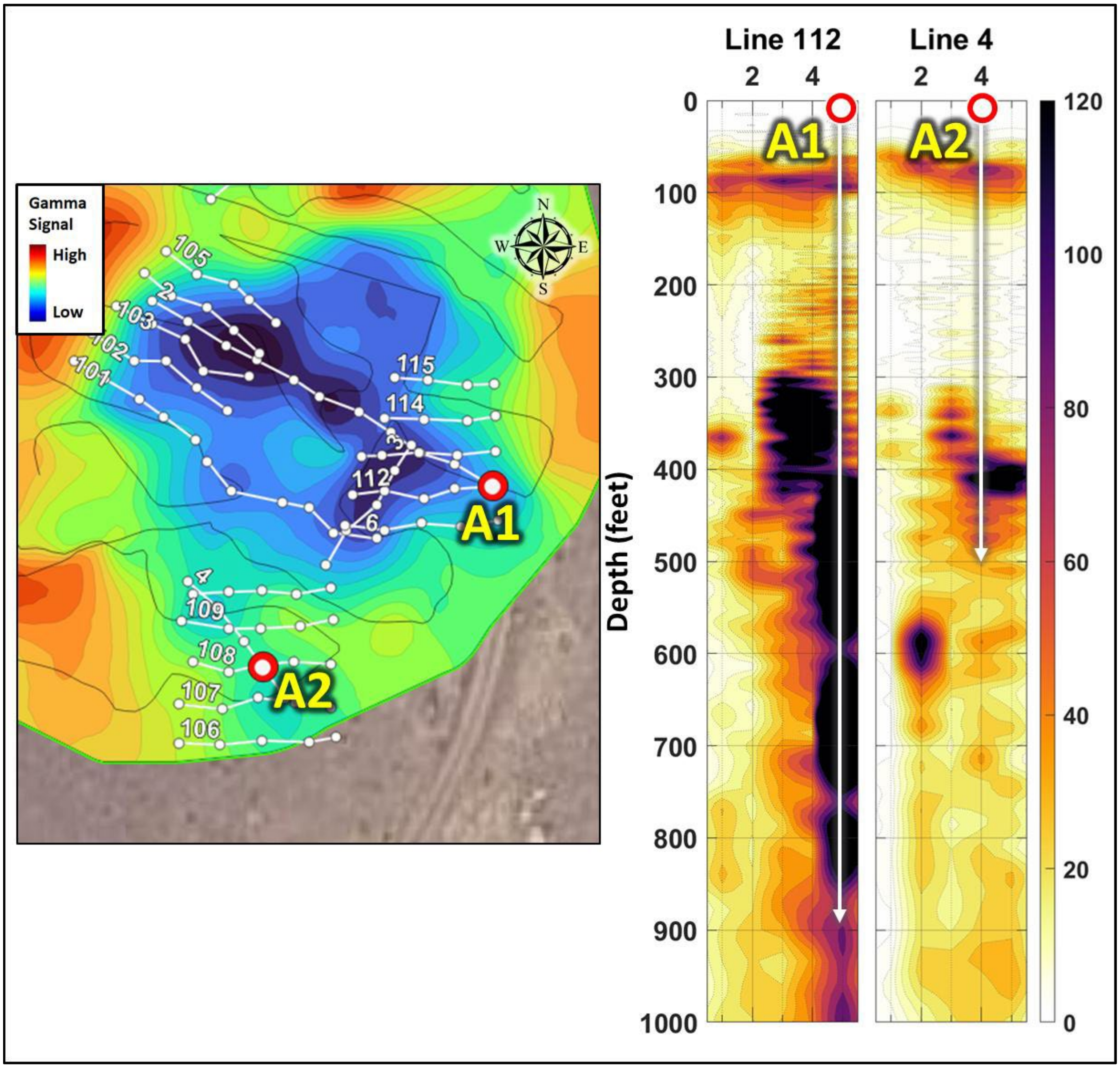


Figure 11: MSR results on Lines 112 and 4.

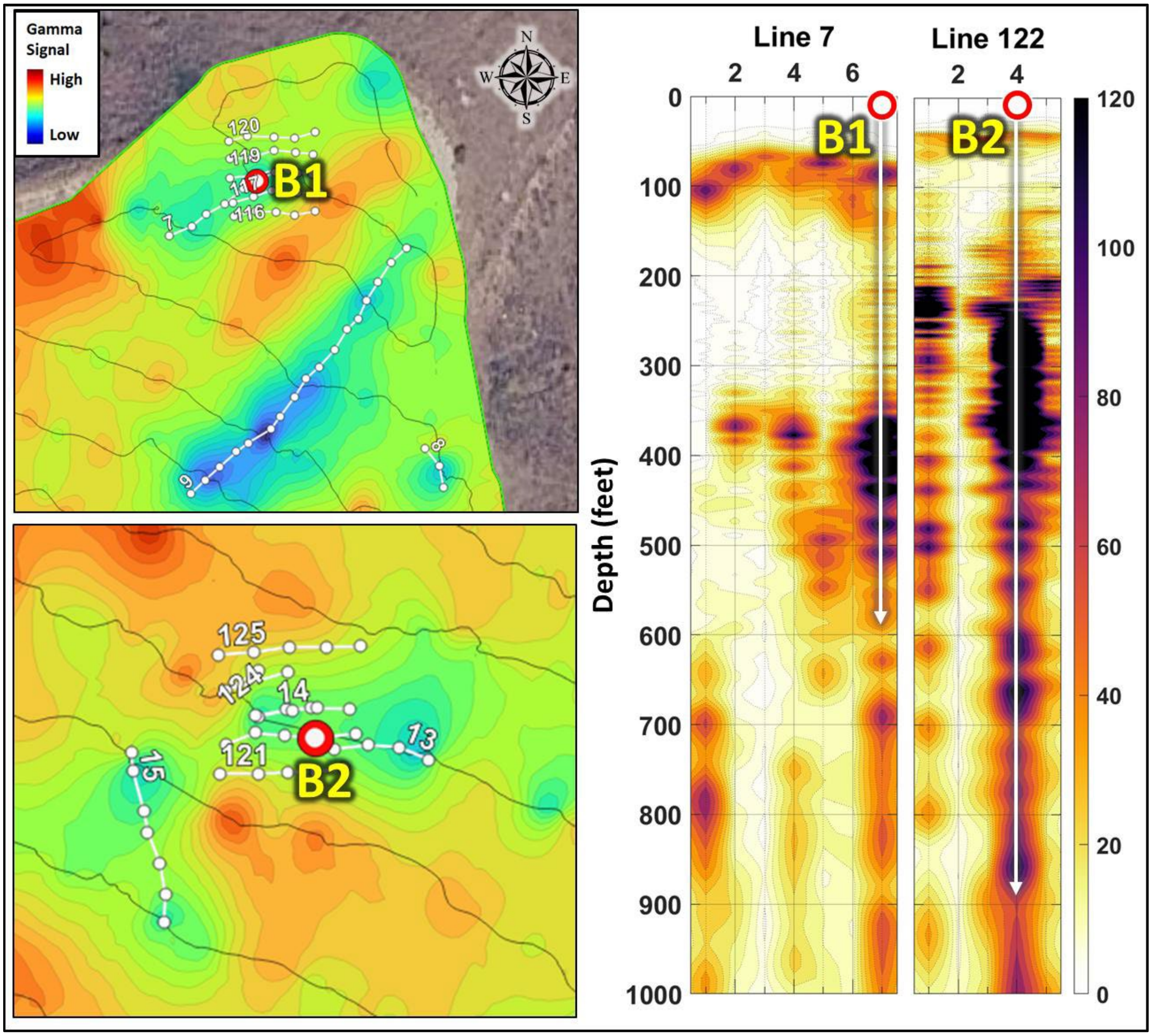


Figure 12: MSR results on Lines 7 and 122.

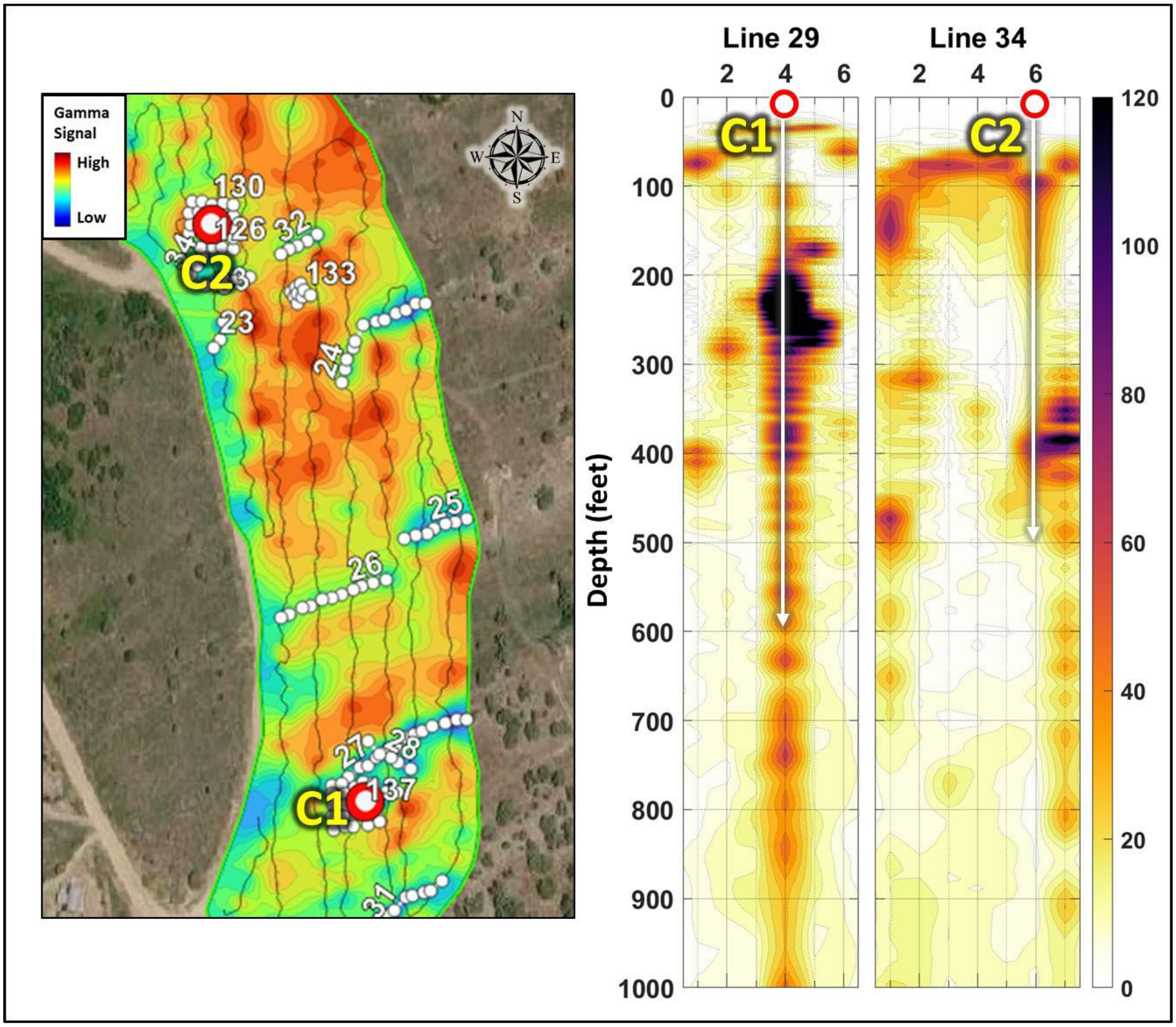


Figure 13: MSR results on Lines 29 and 34.

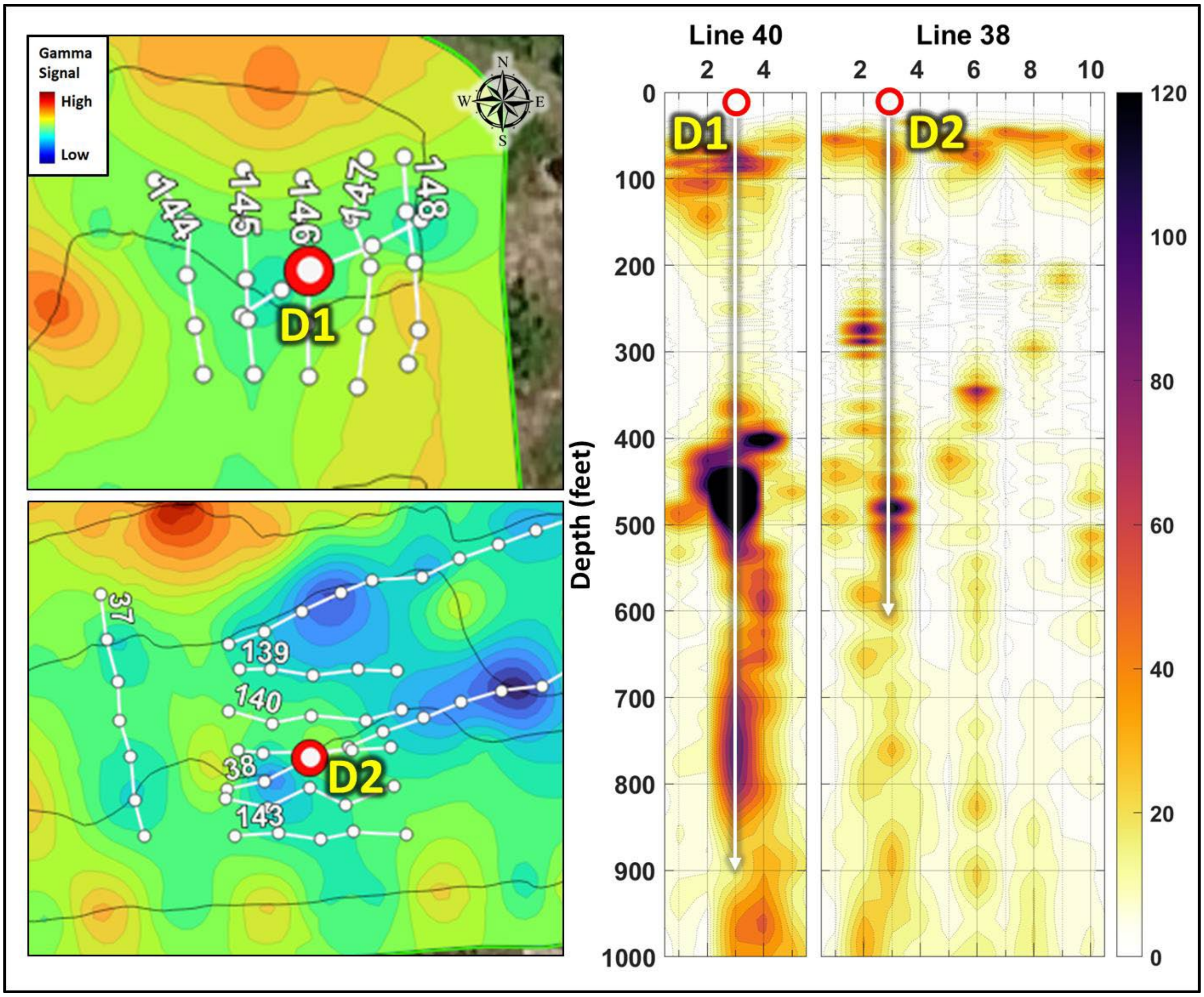


Figure 14: MSR results on Lines 40 and 38.

The prospective targets exhibit a good correlation with gamma patterns, which suggests an increased chance that water occurs in the permeable zones. A1 and A2 exhibit the strongest resonance from about 400 to 850 feet (estimated) and from 400 to 425 feet (estimated) respectively. B1 and B2 exhibit the strongest resonance from about 350 to 450 feet (estimated) and from 250 to 400 feet (estimated) respectively. C1 and C2 exhibit the strongest resonance from about 200 to 275 feet (estimated) and from 100 to 175 feet (estimated) respectively. D1 and D2 exhibit the strongest resonance from about 450 to 525 feet (estimated) and from 475 to 500 feet (estimated) respectively.

In the MSR sections, the very shallow resonance that occurs around 75-100 feet is over-exaggerated because it is caused by the first strong reflection of active energy (hammer) and in most cases is ignored as an exaggerated effect.

Figure 15 presents the MSR results from Lines 103 and 132, collected around an existing wells within the survey area. The depths of the wells are unknown but are shown as dashed arrows to 500 feet. Line 103 occurs in area A and shows resonance from about 350 to 400 feet with minimal resonance at deeper depths. Line 132 occurs in area C and does not show any good resonance over the well location but does have a resonance pocket on the first station from 175 feet to 200 feet.

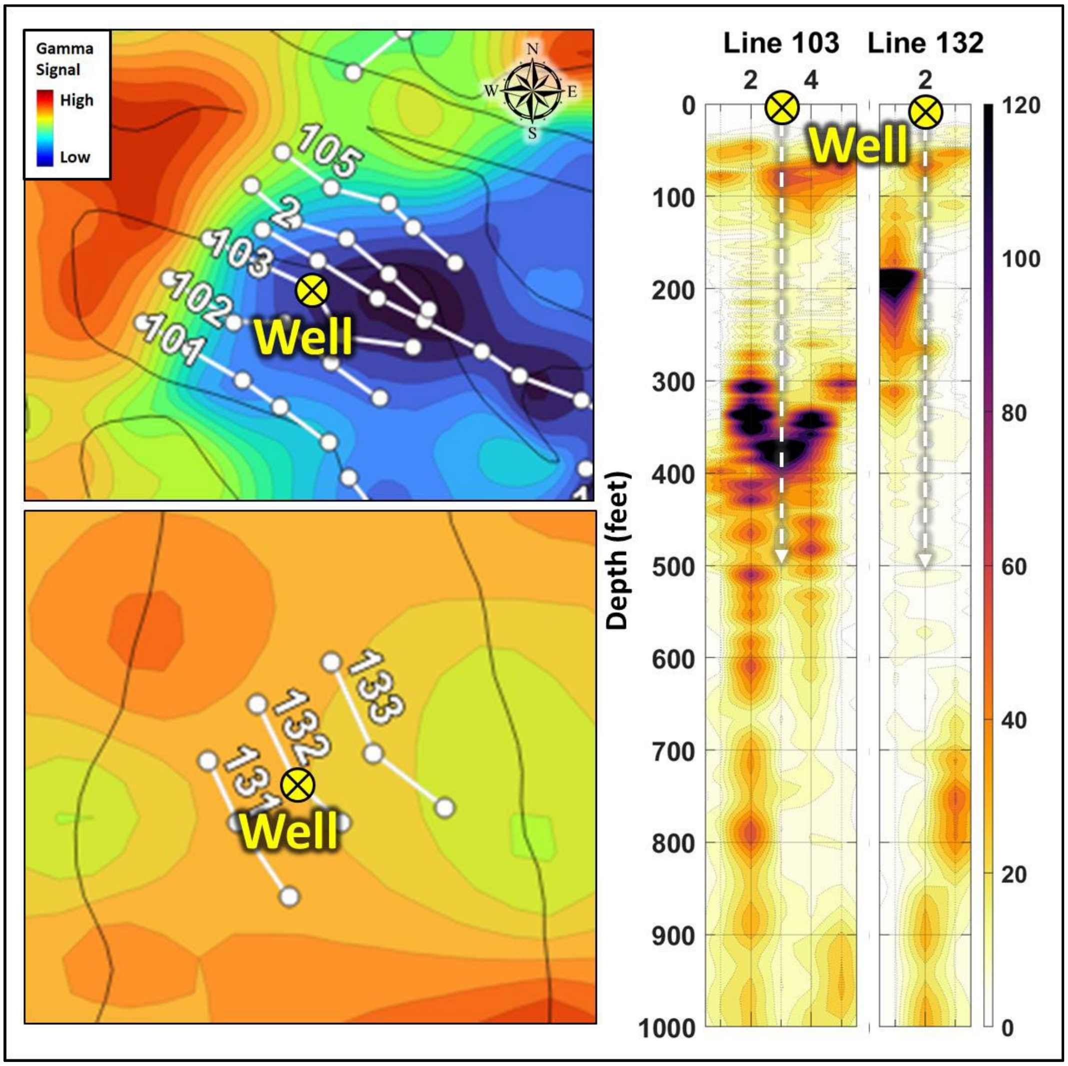


Figure 15: MSR Results from Lines 103 and 132.

Figure 16 shows the MSR resonance values compared to the median value. Keep in mind this plot does not take into account gamma or data from surrounding shots and only provides MSR data from the specific target location. The resonance intensity on these graphs is not a perfect indication of volumetric potential but it does provide some idea. From our experience, the deeper zones of resonance often have greater amounts of water or production capability. The resonance intensities in the target locations are much higher than the background or median (determined from all measurements collected at this site). The majority of this is caused by increased seismic resonance at these particular locations—most likely due to zones of extensional weakness which is likely to include high porosity or fracture zones, meaning greater potential for yielding higher volumes of groundwater.

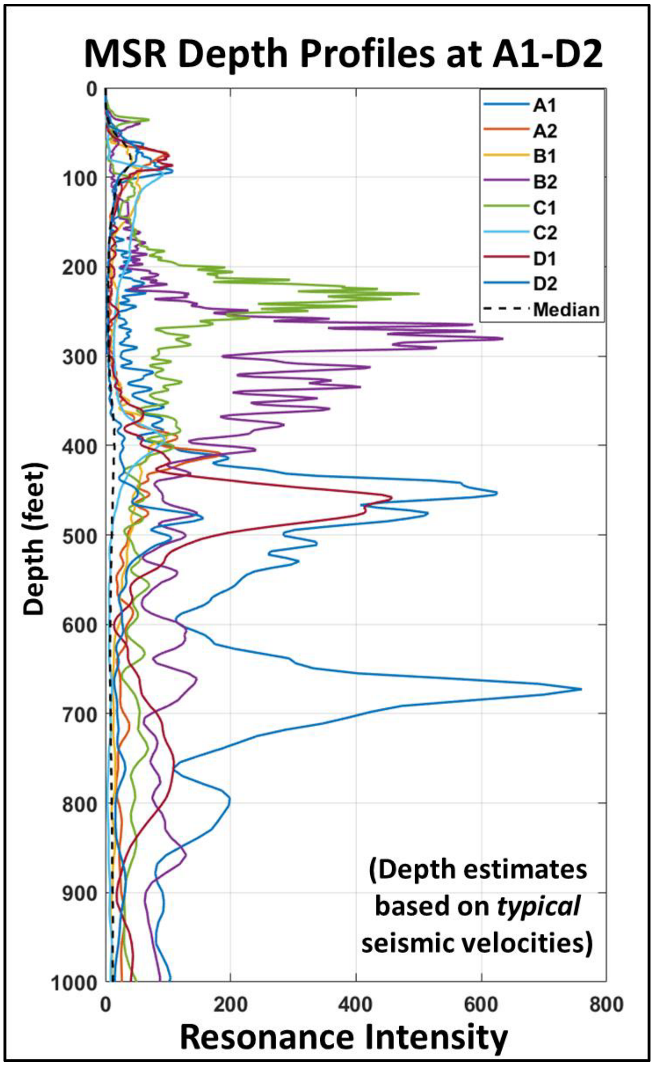


Figure 16: MSR resonance at target locations A1-D2.

3.3 Drilling Risks

Drilling always involves various levels of risks that should be understood in each particular case. Some risks can be reduced, and some cannot. For instance, using best methods of drilling and proper precautions can reduce risks, and a good driller is privy to those things and may also know how to avoid or reduce risk of getting poor water quality which may be known in some areas. Some areas involve high-risk factors that cannot be eliminated even with the best of scientific investigation, such as drilling into thick sequences of mudstone or other very poor-aquifer rocks that are high-risk even when studies help identify zones or fractures. Many have found water in these scenarios and continue to do so, but it is more risky drilling even with good science behind it.

Experienced drillers know that even boreholes in close proximity can produce very differently, and it most cases (unless drilling an "easy" aquifer or "lake" aquifer) the decision of where exactly to place a borehole involves risk. Such risk can be greatly reduced by studies such as this one.

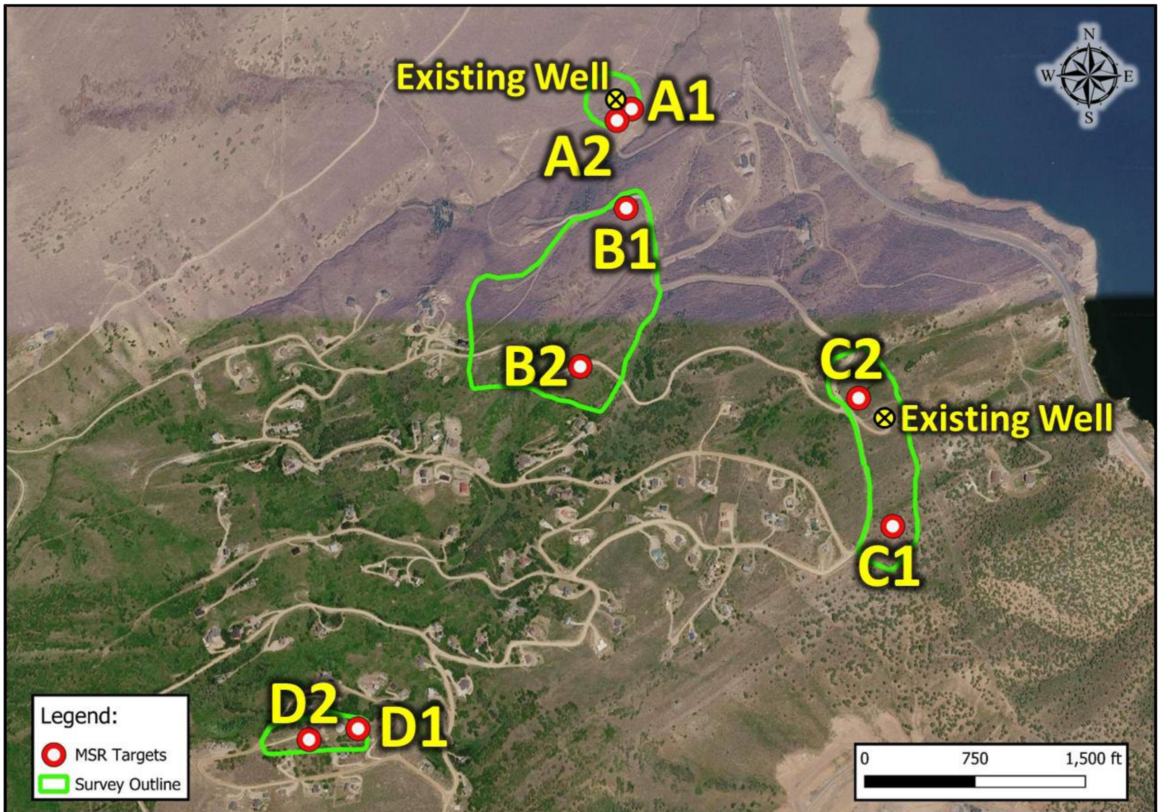
4.0 CONCLUSION

4.1 Summary and Recommendations

This study combined the use of Micro-seismic Resonance (MSR) and Radiometric Gamma in conjunction with traditional geology and lineament studies to ultimately narrow down and pinpoint drill targets within the given study area. This is based largely on microseismic resonance indicators of natural fracture networks that could greatly extend the wellbore reach, especially in subvertical open fracture zones which have been shown in many other cases to support higher-than-average water production. Our experience has shown that targets exhibiting the MSR and Gamma patterns described herein tend to yield higher flow rates of groundwater than average, yet it cannot guarantee such, and exceptions can and do occur. Knowledge of the area from local drillers is often a good supplement to this investigation.

The Gamma and MSR tools were deployed to scout out and narrow down specific locations for prospective drill targets within the total 48.5-acre search area. The target locations, based on MSR shots, are shown in Figure 17 along with a table of coordinates and estimated depth ranges where stronger resonance intensities occur.

Keep in mind that while the tools used for this investigation can provide helpful data, they cannot directly detect, prove or guarantee groundwater production nor detect subsurface water quality—these can only be proven out by drilling. Weighing in driller knowledge of the local area can be very helpful. In comparison to hundreds of other projects where these techniques have been applied, the risk in this case is higher than most.



Target ID	Best MSR Depth Ranges* (ft)	Line#	Shot#	UTM Zone 12 Coordinates (WGS84) Easting m	Northing m	Topo Elev ft	Lat/Lon Coordinates (WGS84) LAT	LON
A1	400-850	112	5	465249	4513606	6135	40.772694	-111.411786
A2	400-425	4	4	465219	4513582	6134	40.772479	-111.412143
B1	350-450	7	7	465243	4513403	6234	40.770863	-111.411853
B2	250-400	122	4	465143	4513073	6422	40.767884	-111.413017
C1	200-275	29	4	465790	4512742	6427	40.764931	-111.405327
C2	100-175	34	6	465720	4513007	6372	40.767318	-111.406181
D1	450-525	40	3	464683	4512322	7113	40.761106	-111.418423
D2	475-500	38	3	464582	4512300	7114	40.760898	-111.419625

***Based on average seismic velocity estimates**

Figure 17: Recommended Drill Targets

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6.0 APPENDIX