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Compartmentalization of Ground Water In An Intermountain Basin: Implications on Performance-Based Landfill Design and Monitoring in the Arid American West

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Abstract

We use five lines of independent evidence to show that shallow groundwater under a landfill location in an arid Wyoming intermountain basin occurs within disconnected compartmentalized perched zones. Test holes intersected water within lenses of silty sandstone, encased by dry clayey siltstones. Ground penetrating radar and seismic reflection geophysical studies identified no continuous water table within the upper ~150 feet of sediments--the regional water table must be at a minimum of 200 feet deep. Tritium activity and stable isotopic composition of the ground waters and carbon-14 age of dissolved inorganic carbon combined show that the water sampled from the monitoring wells recharged as precipitation thousands of years ago under drier conditions than found now. Nearly constant water levels in monitoring wells after snowmelt show modern precipitation does not meaningfully recharge the pockets of groundwater.

The governmental agencies that regulate the design, remediation, and monitoring of municipal solid waste landfills in western arid lands need to explicitly recognize that arid zone hydrology differs from the hydrology in humid, water-rich areas. At the very least, shallow geophysical methods and isotopic age dating of ground water should be coupled to the standard regulatory data obtained from monitoring wells to avoid "false positives", wherein a groundwater resource may be assumed present, but in reality, does not exist. Isotopic methods also can scientifically test if high concentrations of dissolved inorganic solutes measured downgradient of landfills show actual contamination, or alternatively, the natural results of water rock chemical reactions within isolated perched water compartments.

Introduction

Arid zone hydrology differs profoundly from the hydrology in humid regions. In humid regions, precipitation exceeds the combination of potential evaporation and plant transpiration and regional water tables occur as subdued replicas of the surface topography. Where soils in humid regions contain silt and clay, the regional water table can occur within a few feet of the land surface and the water in most soils and rock below the water table can be assumed connect hydraulically to streams and wetlands (e.g.

Winter et al 1999). Recharge to shallow aquifers in the humid east of the United States is on the order of tens of centimeters of precipitation equivalent (e.g. Nolan and others 2007; Prinos and others 2002).

In stark contrast to humid regions, regional water tables in the arid west do not necessarily mimic surface topography because local precipitation recharge provides too little water to maintain high water table elevations under topographically high areas. Recharge to western aquifers mostly occurs during snowmelt from water that fills rivers discharging from mountains and then moves across intermountain alluvial and basin fill sediments. River bed leakage provides most of the water to aquifers in these basins (e.g. Hanson 1991; Scanlon and others 1997, 2006).

Moreover, in arid regions, the amount of modern recharge that replenishes water table aquifers distant from mountain margins appears to be small to negligible in the context of modern climate and human time frames. For example, most of the water in aquifers throughout the American Southwest may be thousands of years old (e.g. Scanlon and others; 1997, 2006, and references cited therein). Except immediately adjacent to active rivers, recharge to most regional ground water systems in the arid American west has not occurred since glaciation, thousands of years ago.

The soils and rocks that can store and transmit water within the alluvial and fluvial sediments that fill western inter-mountain basins consist of sand and gravel deposits (sometimes lithified to rock) commonly isolated from each other by clayey and silty deposits. For example, in the San Juan and Raton basins of New Mexico and Colorado, compartmentalized saturated sand aquifers within ancient deltaic deposits contain ground water literally recharged millions of years old (e.g. Phillips and others, 1986, 1989; Snyder and others, 2003; Reise and others, 2005). In the Powder River Basin of Wyoming, both shallow and deep ground water in the interior of the basin may be thousands of years old (e.g. Bartos and others, 2002).

The compartmentalization of permeable sediments within alluvial sediments in arid and semi-arid western intermountain basins also leads to perched water tables well above the regional water table connected to major rivers. In the case of perching, clayey dry soil or rocks encase saturated pockets of water in materials with larger pore spaces. Precipitation only can replenish perched zones through cracks or fractures during snowmelt. At other times of the year, precipitation either evaporates or sorbs to soil particles to meet the soil moisture deficit in the upper few feet below the water table.

In this paper, we report the results of a comprehensive study to address the hydraulic and geochemical consequences of shallow perched and isolated ground water within thick clayey valley fill deposits ubiquitously found between Rocky mountain ranges from Montana to Nevada. Numerous municipal solid waste landfills have been located in this hydrogeologic setting. Current regulatory practice related to these landfills may need to be reassessed if the shallow ground water found under them occurs in perched and isolated compartments with limited extent and minimal beneficial use.

The hydrologic and geologic results we present summarize over 10 years of investigation done under regulatory supervision by the State of Wyoming Department of Environmental Quality (WYDEQ) (Inberg Miller; 2005, 2008, 2009), and with the addition of special geochemical studies under WYDEQ compliance standards except for isotopic analyses for which there are no regulatory protocols.

Study Area and Methods

Our study area, called the Sand Draw site, occurs southeast of Riverton, Wyoming. There, ancient streams deposited horizontally layered claystone, siltstone, and dense sandstone as the Wind River and Indian Meadows geologic formations that filled an intermountain basin located between the Wind River and Owl Creek Mountain ranges. Similar sediments, thousands of feet thick, fill basins between mountain ranges throughout the Rocky Mountain west from Montana to Mexico. For over 60 years (e.g. Love 1948), geologists have recognized that the Wind River and Indian Meadows formations consists of highly heterogeneous and discontinuous lenses of silty sand, claystones, and siltstone observable even at outcrops at the land surface.

Sand Draw includes a partially-developed municipal solid waste landfill for Fremont County (WY) and occupies an interfluvial topographic plateau located between ephemeral tributaries to the Little Wind River, located about 12 miles away. These ephemeral streams and associated gullies radiate outward from the plateau (Fig. 1). Under topographically high areas, such as Sand Draw, potable water in the Wind River and Indian Meadows formations occurs hundreds of feet deep (Whitcomb and Lowry 1968).

To characterize subsurface water near the land surface, we drilled 24 test holes less than 150 feet deep. These holes were completed as water table monitoring wells (Inberg and Miller; 2005, 2008, 2009). Some test holes did not penetrate into a saturated zone. Others filled with water only after several months after drilling. Water elevations were measured monthly. If monitoring wells intersect a continuous water body that can be replenished (recharged) today, water levels should vary seasonally and rise as snowmelt enters the groundwater flow system.

We obtained electrical earth resistivity data (Fink and others 2009) along 34 transects across the study site forming a grid with NW and EW lines separated by about 100 feet. Resistivity was recorded by a AGI SuperSting-R8 and evaluated using Poly Software International's Pro-Stat Version 4.50a by inverse modeling using AGI EarthImager™ 2-D and 3- D Software packages. Electrical resistivity can determine depth to water and extent of water bearing units within the upper 200 feet of rock. The earth resistivity methods produced a model of the spatial distribution of intrinsic resistivity within the subsurface (Fink and others, 2009).

We also obtained a reflection seismic reflection profile at the landfill site that showed subsurface geologic conditions from 200- 800 feet deep (Bauer and others (2009). The installation of monitoring wells and the extensive geophysical work together determined if a regional water table occurs under the study site within the upper ~150 feet of rock, or alternatively, if water occurs in discrete, disconnected and perched compartments.

We collected samples of ground water from the monitoring wells in summer 2008 to measure concentrations of major dissolved solutes (less than 0.45 microns) and the isotopes of water and dissolved inorganic carbon. The combination of solutes and isotopic measurements provide a potent forensic tool to distinguish the hydrodynamics and timing of recharge to aquifers (Ali and others 2009; Mazor 1990). We also measured field pH and specific conductance. Since we anticipated perched and isolated water bodies, we hypothesized that chemical variations in the water quality would not reflect that expected if ground water moved across the study site along continuous subsurface flow paths. Rather, we anticipated that chemical concentrations would vary as a function of how long the water had been in contact with the rock and local rock mineralogical composition, and be unrelated to water level elevations.

We obtained the stable isotopic composition of the groundwater using standard mass spectrographic methods at the University of Waterloo (Ontario). Environmental Isotopic Laboratory (http://www.uweilab.ca/). The precision of isotopic measurements for oxygen ($\delta^{18}O$) and hydrogen of water (δD) were +/- 0.05 and 1 o/oo respectively. Stable isotopic measurements are reported in part per mil notation references to the internationally accepted standards VSMOW (for water). Stable isotopes can determine if ground water infiltrates and replenishes groundwater supplies under modern climatic conditions.

We obtained carbon-14 dates of the dissolved inorganic carbon and stable carbon isotopic ratio through Beta Analytic Laboratories (http://www.radiocarbon.com/) by accelerator mass spectrometry (AMS). We also measured the radioactive activity of tritium, another isotope of water through the University of Waterloo Environmental Isotope Laboratory. Precision for the carbon isotopic ratio ($\delta^{13}C$) was +-0.05 o/oo, +/-0.1 tritium units (TU) for tritium, and +/-0.05 percent modern carbon for carbon-14 analyses. and PDB (for carbon).

We used tritium and carbon-14 activities (a measure of radioactivity) to directly measure when the ground water we sampled entered the landfill area as precipitation recharge. Tritium, H^3, consists of an atom of hydrogen in water that has two extra neutrons. From the late 1950's through the late 1960's, thermonuclear weapons testing in the south Pacific injected into the atmosphere tritiated water vapor with thousands of times more tritium activity than produced naturally.   This radioactive pulse can now be followed as a tracer in groundwater flow systems. Every 12.5 years, tritium activity decreases by half. From tritium activity, we can determine if water in an aquifer entered it during the past 50 years or so. Tritium activity less than 2 TU indicates precipitation recharge essentially prior to the thermonuclear atomic testing that began in 1952 (http://wwwrcamnl. wr.usgs.gov/isoig period/h_iig.html; Clark and Fritz 1997).

Carbon-14 is produced in the high atmosphere naturally by the bombardment of nitrogen by cosmic radiation. The half-life of this isotope is about 5,200 years. Carbon-14 naturally enters the earth's surface carbon cycle, including the food chain. Plants incorporate some of this naturally radioactive carbon as part of their tissues, which then become mineralized back to carbon dioxide and water when the plants die and decay. The amount of carbon-14 found in living plants and animals remains constant because carbon lost as respiratory and other waste products continually is replenished by photosynthesis and consumption. But, when precipitation passes through the soil zone and recharges the water table, the carbon-14 in the dissolved carbon dioxide can no longer be replenished. From that point on, the amount of the radioisotope remaining in dissolved inorganic carbon can be used to also determine when the ground water was recharged by precipitation (e.g. Clark and Fritz 1997

Raw carbon-14 radioactivity operationally is converted to "percent modern carbon", which can be converted to carbon-14 groundwater age (Clark and Fritz 1997). In practice, accurately calculating when recharge occurred from carbon-14 activity can be complicated because of chemical reactions that occur when the dissolved carbon dioxide in the ground water reacts with minerals, and in some places, ancient organic matter (e.g. coal). Without taking these processes into account, the measured carbon-14 age only is "apparent age", because the water may be somewhat younger. Because of the potential complexity in getting accurate dates, some regulatory agencies view ground water age as semi-quantitative. For example, the State of Minnesota classifies its ground water as "recent, mixed, and vintage" based on tritium and carbon-14 analyses (http://www.dnr.state.mn.us/waters/groundwater_section/mapping/status.html). We chose to use a similar classification and approach for the purpose of this paper to determine if recharge to ground water at our study site occurs now, happened within the last hundred years, hundreds of years ago, or thousands of years ago.

We used both MINITAB™ and EXCEL™ statistical packages to determine the extent to which water level changes in the monitoring wells over time reflect recharge from snowmelt and storms during the study, and to prepare semilogarithmic plots of water chemical composition.

Results

Hydrogeology

The 24 test holes (Table 1) drilled at the site not unexpectedly penetrated a complex sequence of lenticular, layered claystones to sandy siltstones (Inberg-Miller 2005, 2008, 2009) typically found in alluvial fan deposits. Seven monitoring wells installed in test holes produced no water, implying that the suction head of water found in the penetrated unsaturated sediments exceeded that needed for gravity-driven flow through effective porosity (connected pores) (Tindall and Kinkel 1999).

No continuous water-bearing zone occurred: some wells within the study area remained dry at the same well point elevations as those that had water. Water levels in wells drilled at the highest part of the study area occur at higher elevations than those on the flanks, which initially suggested the water might reflect a shallow continuous "potentiometric surface" (Inberg Miller 2005, 2008, 2009). However, water did not occur in any identifiable continuous saturated strata, but rather, entered where screens intercepted sandier rock within unsaturated dry claystones.

Water level elevations varied strikingly between wells. For example, water levels differed by about 35 feet between wells R-10 and R-14D, only 630 feet apart. Wells R-9S and R-9D horizontally are only 55 feet apart, yet the first occurrence of water in them differs by nearly 7 feet. The water level drop was fully 100 feet between MW-R20, completed in silty sandstone, and that in sandy siltstone at MW-R21, 400 feet away.

Water levels in monitoring wells from 2001 through 2009 (Figure 2) show little or no seasonal change. Although the lack of water level variation over time in individual wells at Sand Draw seems clear from simple observation, correlation and step-wise regression also mathematically showed that water level changes in paired monitoring wells do not correlate with any statistical significance (Hedges and Groutage 2005). The lack of correlation show that the monitoring wells do not intersect the same aquifer (e.g. Prinos and others 2002)

Geophysical Analysis

The deep seismic reflection study compellingly documented discrete and heterogeneous lenses of alluvial sediment, similar to that observable in outcrop, persisting from 200-800 feet deep in the subsurface (Bauer and others 2009). In the upper 200 feet, most earth resistivities fell between 10 to 20 ohm-meters, a very narrow range. Figure 3 shows the result of fitting multiple probability density functions to the overall resistivity population including; one very-high-count showing the bulk of the resistivity population, and three relatively low-counts; "Low range", "Middle range", "Med-high range". Statistically, the principal population describes the resistivity of the entire area surveyed. The other populations may be present, but because of their relatively low count, can only be considered ancillary to the principal population. What conductive horizons that exist differ only by a few ohm-meters from an otherwise much broader conductive zone that pervades the entire study site. Figure 4 shows a representative west-east transect colored by resistivity. Electrically conductive subsurface regions appear as cool hues (blue to green) and resistive regions are represented by warm hues (orange to red). But, note that the range of resistivity remains very small and no clear discrimination of heterogeneities can be seen.

Geochemical Analysis

Major Solutes

Table 2 presents the results of the geochemical analyses in milligrams per liter along with isotopic values for water and dissolved inorganic carbon. We took these data and converted the concentrations of major dissolved solutes reported into millequivalents/L, a geochemical normalization approach designed to classify different water types by prevalence of dissolved solute species. Figure 5 shows a plot these concentrations to fingerprinting of water types (Mazor 1991). In this format, the lines connecting the solutes in each analysis define a diagnostic shape, which geochemists use to determine how groundwater chemistry evolves along flow paths. Using a semi-logarithmic vertical scale spreads the data out so differences can be clearly seen. In general, ground water samples from the study site can be classified as sodium bicarbonate type waters.

Isotopic Measurements

Except for water in MW-11, tritium activity falls below the 2 tritium unit USGS cutoff for essentially background tritium values. Carbon-14 activities for water sampled from 4 wells show conventional carbon ages more than 2,000 years.

We plotted the isotopic ratio of oxygen (O16/O16) against that for hydrogen in water (H2/H) along with values for water in the Wind River (Coplen and Kendall 2000) to determine if the sources of the water occurred under similar climatic conditions (Figure 6). The stable isotopic composition of water and streams when plotted on such a diagram define what geochemists call a "local meteoric water line" (LMWL) (e.g. Clark and Fritz 1997). The stable isotopic composition of the sampled ground waters plot below the LMWL defined by the Wind River and for shallow groundwaters found in clayey deposits near a river in Fremont County where Sand Draw occurs (Jin, L. 2008).

Interpretation

The multiple independent lines of geologic, hydrologic, and geochemical evidence gathered at Sand Draw, a typical intermountain location in Wyoming and elsewhere in the American west, all point to compartmentalization of water in perched and discontinuous zones. Perched groundwater consists of a small water-bearing zone underlain and overlain by rock porous media. Perched ground water is not part of a regional water table connected to surface water bodies.

Test Drilling and Geophysics

Test hole drilling identified no continuous permeable horizon across the landfill site. These results agree with the results of the earth resistivity survey. The range of absolute measured values for resistivity showed a stratigraphic section notably rich in silt and clay with no clear continuous saturated zone or permeable zone within the upper 150 feet of sediment. The site is underlain by massive, electrically conductive clay-rich sediments containing localized perched water bodies in slightly-higher-permeability sediments.

The clay-rich sediments form a very low permeability environment that minimizes infiltration from precipitation. The earth resistivity measurements show no interconnected water bearing lenses. The lack of a low conductive zone at the base of the penetration of the resistivity survey also suggests that the regional water table under Sand Draw much be at least 200 feet deep. This earth resistivity geophysical interpretation also agrees with the results of reflection seismic reflection studies at Sand Draw done by hydrogeology students from the University of Missouri Geology Field Camp in 2008 (Bauer and others 2009). These reflection studies were done along an east to west transect across the study site and reflection images were calibrated against materials found in the test holes drilled for the monitoring wells. The reflection geophysics clearly identified discrete lenses of sandy mudstones encased in claystones at depths below 200 feet and also was unable to identify a water table across the site within the upper 200 feet of strata. Fundamentally, the geophysics and geologic test holes showed water encased and compartmentalized in sandy lenses under Sand Draw. This compartmentalization is not unexpected, given the well-known formational heterogeities associated with the Wind River Formation (e.g. Whitcomb and Lowry 1968).

The variability in water level elevations across Sand Draw also document isolated perched compartments. The measured decrease in water level elevations from the top of the Sand Draw plateau to its sides produces an unreasonably steep water table hydraulic gradient (slope) of up to almost 25%, if it were assumed that the wells tapped a single hydraulically connected water body. Hydraulic gradients occur on the order of a few percent, not tens of percent except along steep mountain alluvial fans and other large scale sloping geomorphologies--not in dissected terrains of horizontally laid rocks and sediments (e.g. Freeze and Cherry 1979).

Most recharge to regional water tables in arid Wyoming and elsewhere in the arid west occurs at snowmelt and during spring rains (Scanlon and others 2008). During the rest of the year, infiltrating rain never reaches aquifers because of evaporation caused by high temperatures and low humidity. The University of Wyoming estimates that less than a couple of centimeters of water per year recharges the regional water table in non-mountainous regions of Wyoming, except adjacent to rivers (http://www.sdvc.uwyo.edu) There, rivers lose water to underlying aquifers and recharge the adjacent regional water table when river stages rise.

This seasonal recharge to regional water tables can easily be seen in well hydrographs of water levels where ever it occurs. For example, the U.S. Geological Survey maintained an observation well over 400 feet deep in the Wind River formation from 1957-1984 (site 430051108240901). Water levels in the well, local near the Little Wind River, about 15 miles from our study site, systematically rise tens of feet with spring snowmelt recharge and then decline during the summer and fall (http://nwis.waterdata.usgs.gov/). In contrast, the comparatively small water level changes in monitoring wells at Sand Draw (on the order of tenths of a foot) appear random, unrelated to recharge at snowmelt, and perhaps may be related to barometric response of water under confinement or even measurement error.

Geochemical Analysis

Variations in the concentrations of major solutes and isotopic tracers can independently test conclusions on hydrogeologic conditions based on geological, geophysical and water level information. The major mineralogical composition of the rock formations under the Sand Draw landfill site consists of quartz, calcite, secondary gypsum, and ion-exchangable clays that can serve as natural water softeners. These minerals derived and formed from the shedding of eroding sedimentary and igneous rocks from the Wind River Range to the west as it uplifted tens of millions of years ago.

The clays in the Wind River Formation remove hardness (calcium and magnesium) in water and replace it with sodium.

Concentrations of dissolved solids should increase down presumptive flow paths within a aquifer with moving ground water as minerals continually dissolve to equilibrium. If concentrations do not increase in the presumptive direction of groundwater flow, local recharge has diluted the water, or the water occurs in compartments effectively isolated from each other. Water levels at Sand Draw are greatest at monitoring well R-8 at the top of the plateau. But, the concentrations of total dissolved solutes in water sampled in wells having lower water level elevations than in R-8 both decrease *and* increase. For example, total dissolved solids in water decrease from R-8 from 3320 mg/L TDS to 516 TDS at R-10, but *increase* with distance to 6290 mg/L at R-20 (Table 2; Figure 1). Concentrations of dissolved solids that change both up and down along presumptive flow paths do not agree with what would be geochemically expected from first principles --if all wells were screened in a continuous aquifer over this small geographic area. Therefore, the differences in the chemistry must be unrelated to flow paths, and be due to local chemical equilibrium between water and the particular minerals the water contacted within different and isolated water-bearing compartments.

Radiogenic Age Dating of the Water

Except for one sample, tritium values fall below what the USGS considers mostly background tritium activity, <2 tritium units. Most of the water in the wells must have recharged *at least* 60 years ago. Tritium activity in water sampled from R-11 was about half that now measured in precipitation (Ottawa site, IAEA, http://www-naweb.iaea.org/), between 10 and 20 tritium units. Here, either some water recharged the water-bearing zone after 1952, or drilling fluids may have entered the well when it was drilled. This single outlier aside, the tritium data all show little water has reached the water bearing zones since the 1950s-1960s, fully half a century ago (http://www.sdvc.uwyo.edu/groundwater/). These tritium ages agree with tritium ages for ground water sampled from similar clayey sediments in basins elsewhere in Wyoming (Bartos and Ogle 2002).

All groundwater ages based on AMS carbon-14 activity suggest that the water sampled at Sand Draw recharged over 1,000 years ago (Table 4). Determining the exact time when precipitation recharged the ground water from carbon-14 activities is difficult because chemical reactions in the aquifer can add carbon having no carbon-14, and "dilute" the age measurements. This dilution would make the water seem older than it really is (Clark and Fritz 1997). However, the uncorrected *order of magnitude* of carbon-14 ages of the waters at Sand Draw cannot plausibly change with geochemical calculations to account for water-rock interactions.

For example, geochemists commonly double the value of modern carbon and thereby halve the apparent age to provide a first approximation to adjust for carbon-14 "dead carbon" from dissolving carbonate minerals (e.g calcite), if present, in soils or an aquifer (e.g Clark and Fritz 1997). Doing this simple calculation for the carbon-14 dates for Sand Draw still produces recharge thousands of years old.

Stable Isotopes of Water

In the mountainous regions of the American west and the north-central and northeastern United States, glaciers emplaced melt water over 10,000 years ago into permeable rocks and soils. These waters can be identified by water isotopic ratios smaller values than modern recharge on local meteoric water lines defined by the stable isotopes of water (e.g. Siegel 1991; Siegel and Anderson 2000). In contrast, if recharge water entered an aquifer from a surface water body or from soils from which significant evaporation occurred, the water would isotopically have greater values than modern recharge (the "lighter" water molecules preferentially evaporate) and also define a trend at an acute angle to the modern local meteoric water line (Clark and Fritz 1997). Should such a line occur, its intersection with the LMWL defines the isotopic value for the original water before it partially evaporated (Clark and Fritz 1997).

Snowmelt mostly recharges Wyoming aquifers today because evaporation and plant use of water in the summer does not allow summer storm water to recharge. At Sand Draw, the isotopic composition of the ground water not only plots *below* the Wyoming local meteoric water line (e.g Benjamin and others 2005), but also below the isotopic composition of the Wind and Yellowstone Rivers, which show an evaporative trend intersecting the local water line at about the -20 o/oo +/- 1 oxygen isotopic value (Figure 6). This value falls near that of average snowmelt and shallow ground water in clayey soils in the Wind River Range near Lander (Jin 2008).

Extending the trend of Sand Draw groundwater isotopes to intersect the meteoric water line leads to a recharge value of about -24 o/oo, prior to evaporation and far smaller than what would be expected from snowmelt recharge now in the Riverton area. Values less than -21 o/oo for the oxygen isotopic ratio in ground water compare well to glacial melting ice or rain which recharged aquifers under much colder times than today, thousands of years ago (e.g. see review in Person and others 2006).

Why the rain and snow that once fell on Sand Draw, located on a topographic divide, became evaporated before it entered the compartmentalized water bearing zones remains unknown. Perhaps the time it took for these waters to infiltrate allowed evaporation from the water table to persist sufficiently to develop the clear evaporation signal. Whatever the cause, the stable isotopic data also show that water in the isolated compartments in the study area clearly differs from that of precipitation, or even in Wyoming rivers today.

Summary and Conclusions

Fundamentally, the combination of: 1.) tritium and carbon-14 age dating, 2.) groundwater geochemistry, 3.) lack of seasonal water levels changes, 4.) lack of a continuous zone of saturation, and the 5.) clay-rich stratigraphy found by drilling and geophysics, independently and together document the hydrologic and geochemical effects that would be expected were the ground water under Sand Draw found in isolated compartments last replenished by precipitation many hundreds to thousands of years ago. Even the location of water in deeper parts of the formation, well below 200 feet deep, may be local, given the strong heterogeneity of the Wind River formation shown by seismic reflection (Bauer and others. 2009). The regional groundwater table under Sand Draw has not been yet found, but probably occurs well over 200 feet deep at about the elevation of the Wind River located about 12 miles away. What water exists under Sand

Draw in the upper 200 feet of rock must be perched, immobile, and isolated from the deeper regional water table by tight and dry rock.

When compartmentalization of groundwater characterizes the subsurface, the concept of contamination to an "uppermost aquifer" becomes moot because compartments of water, such as found at Sand Draw, do not constitute meaningful water supplies in the context of why aquifers may be protected by regulatory agencies. In settings similar to that of Sand Draw, contamination at the land surface cannot move to the compartmentalized water bodies in the subsurface below with in human time frames, unless fractures or secondary pore spaces occur to enable the water to pass through the dry rock and soil without being adsorbed to meet the soil moisture deficit. At Sand Draw, pore water sampled by monitoring wells last recharged the site many hundreds to thousands of years ago. No preferential flow paths occur--otherwise there would be modern water less than 200 feet below the land surface in many places at the site.

Regulatory agencies make decisions on MSW landfill liner designs and landfill remediation based on whether the water table beneath, accessed by humans and ecosystems as an aquifer, can be impacted by waste contaminants. The default condition for engineering a new landfill often relies on a "worst-case" scenario, invoking the precautionary principle. But precautionary worst-case scenarios need to be placed in the context of regional and local climate and hydrogeologic settings to insure that the regulatory decisions are fair and equitable. Title 40 section of the Federal Code of Regulations of the U.S. Environmental Protection Agency (http://www.epa.gov/lawsregs/search/40cfr.html) specifically and clearly recognizes that engineering MSW landfills in the humid wet regions of the Nation may not apply to dry regions with different hydrogeology:

> "It is possible that a MSWLF unit located in an arid climatic zone would not produce from sources of water (e.g. precipitation) other than existing within the waste at the time of deposition. In such an environment, the owner or operator may demonstrate that significant quantities of leachate would not be produced. ....If significant leachate production would not be expected, the regulatory authority, when reviewing the demonstration, should consider the hydrogeologic characeristics of the facility and the surrounding area, in addition to the expected volume of leachate and climatic factors." (p. 124, Chapter 4 Subpart D Design Criteria).

At Sand Draw and logically, within other western and arid intermountain basins filled with Tertiary and Cenozoic age alluvial and deltaic sediments, the only fluids generated by a municipal solid waste landfill logically would be those from biodegradation of the refuse itself. But this process, compared to that found in humid climates, itself inherently would be inhibited by the lack of moisture to enhance bacteriological populations that lead to the decay. Minimal leachate would be produced, compared to MSW landfills in the water-rich regions in the country, and what leachate might be produced would not penetrate deep because of the extreme soil moisture deficit and clay content of the subsurface. Indeed, if water hundreds to thousands of years old remains perched under Sand Draw, it logically would take equivalent time for any leachate to migrate to it--even without a liner system at all.

EPA Chapter 4 Subpart D regulations further state that;

"The design must ensure that the concentration values listed in Table 1 will not be exceeded in the uppermost aquifer at the relevant point of compliance . . . "

The question herein lies in what the definition of an aquifer might be. The Wyoming Department of Environmental Quality's definition of an aquifer is:

"a zone, stratum or group of strata that can store and transmit water in sufficient quantities for a specific use." (Wyoming Department of Environmental Quality, Water Quality Rules and Regulations, Chapter 8).

This definition contains ambiguity, as do all definitions for aquifers. For example, water from one isolated compartment at Sand Draw has been used for washing trucks and equipment--but not for drinking, given its salinity. This water body will not be there for perpetuity, because modern precipitation does not reach it. Does this constitute an aquifer that needs protection? The water in the shallow compartments under Sand Draw logically does not have much meaningful common beneficial use, both in terms of quality and quantity.

We prepared this paper not to discussing how landfills should be designed in the arid west but to put the potential for contamination into scientific perspective to guide future discussion on this matter. For example, the State of Wyoming Department of

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List of Figures

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Figure 1

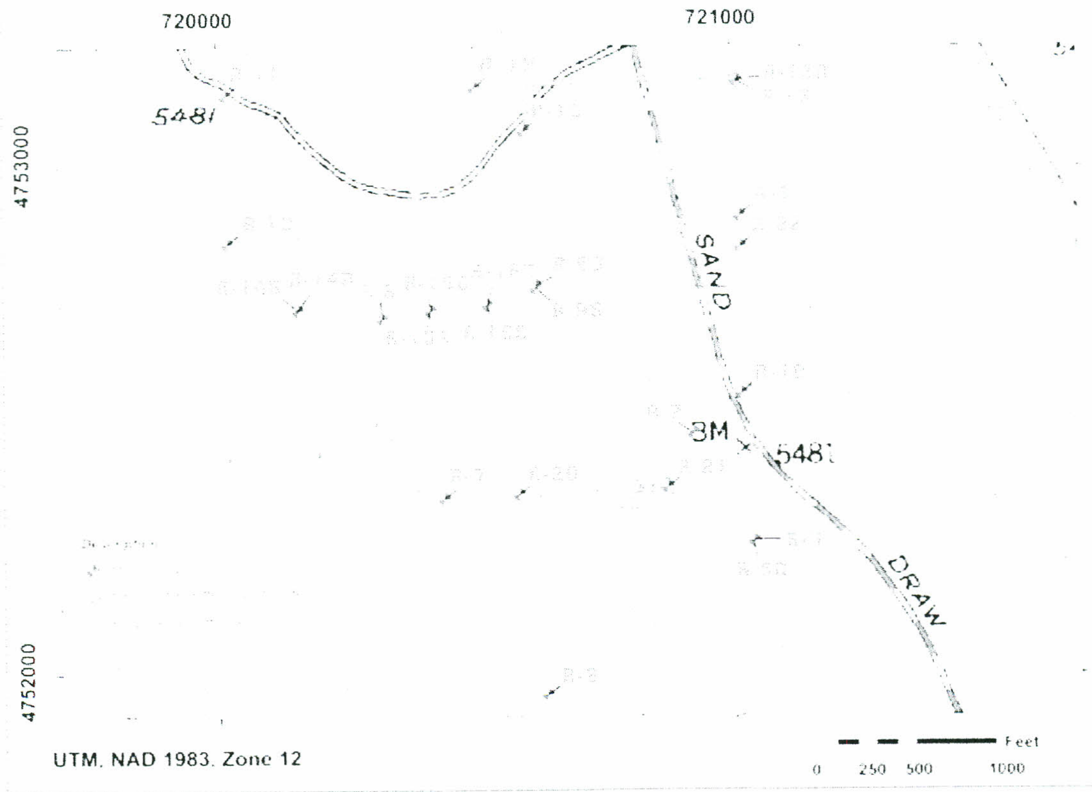
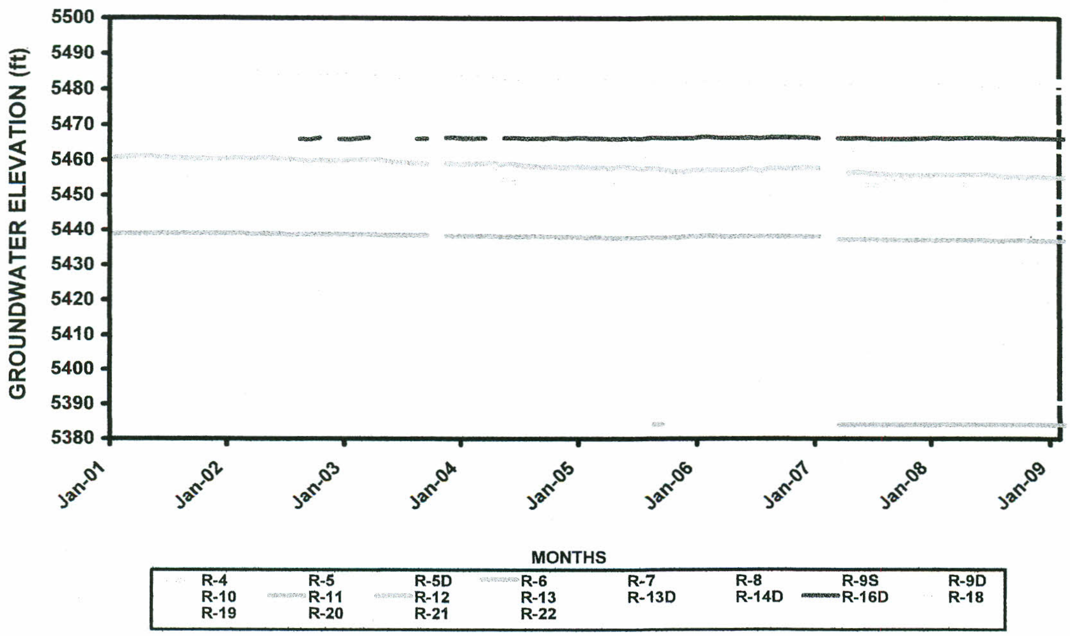
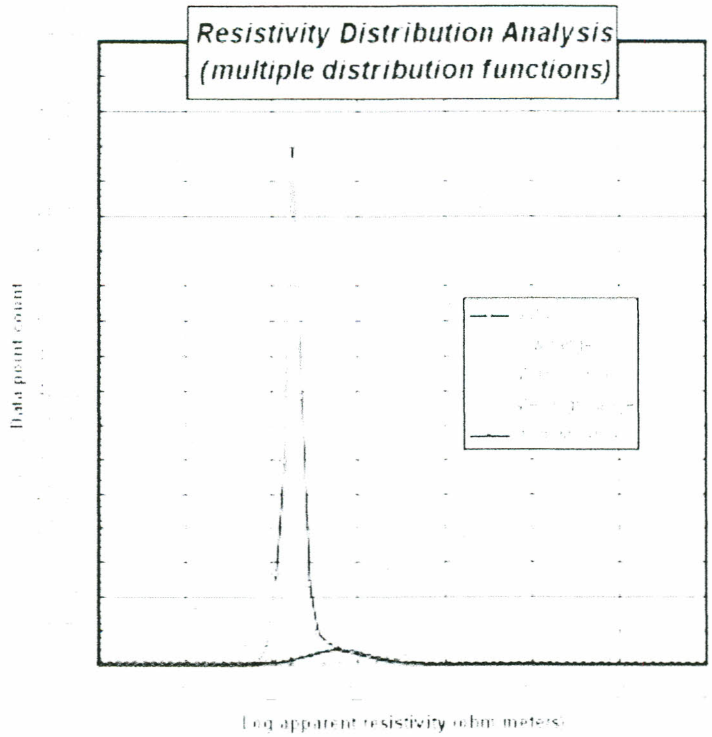

720000
721000
4753000
4752000
5481
SAND
DRAW
BM
5481
UTM, NAD 1983, Zone 12
Feet
0
250
500
1000

Figure 2



GROUNDWATER ELEVATION (ft)
5500
5490
5480
5470
5460
5450
5440
5430
5420
5410
5400
5390
5380
Jan-01
Jan-02
Jan-03
Jan-04
Jan-05
Jan-06
Jan-07
Jan-08
Jan-09
MONTHS
R-4
R-5
R-5D
R-6
R-7
R-8
R-9S
R-9D
R-10
R-11
R-12
R-13
R-13D
R-14D
R-16D
R-18
R-19
R-20
R-21
R-22

Figure 3


Resistivity Distribution Analysis
(multiple distribution functions)
Data point count
Log apparent resistivity (ohm meters)

re 4

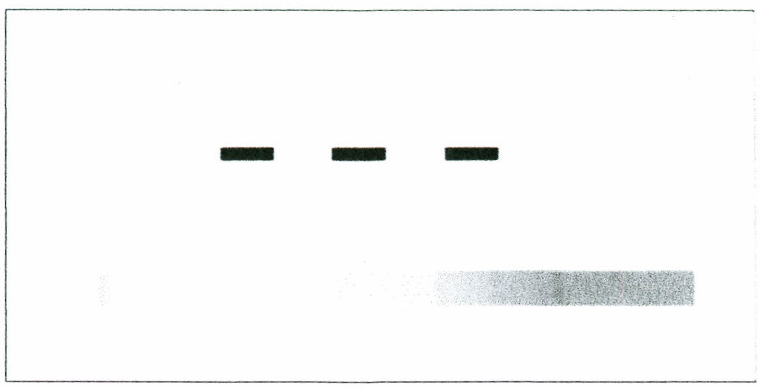


Figure 5

Figure 5

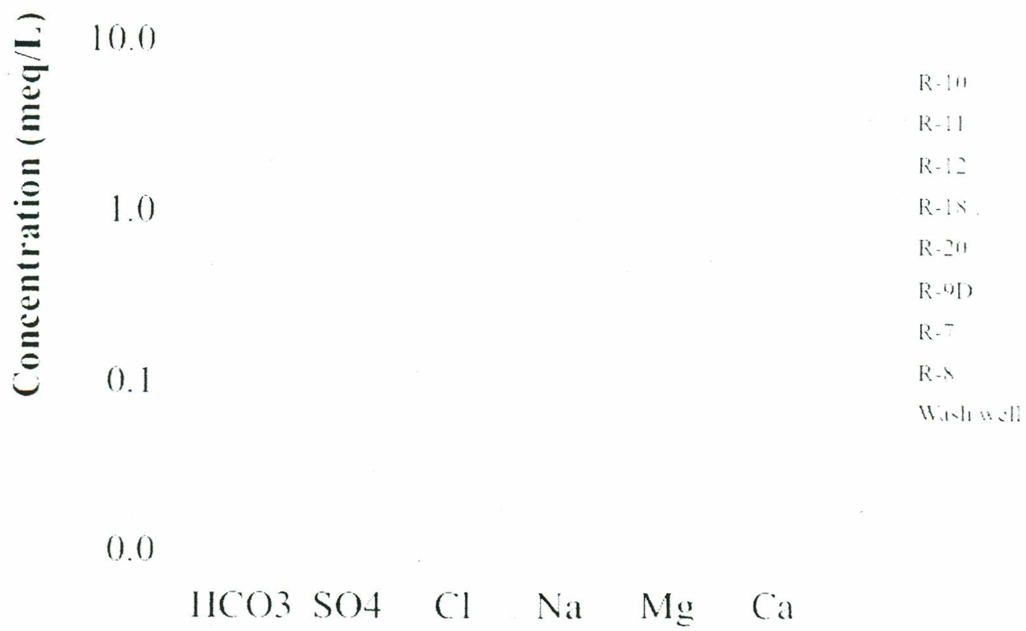


Figure 6

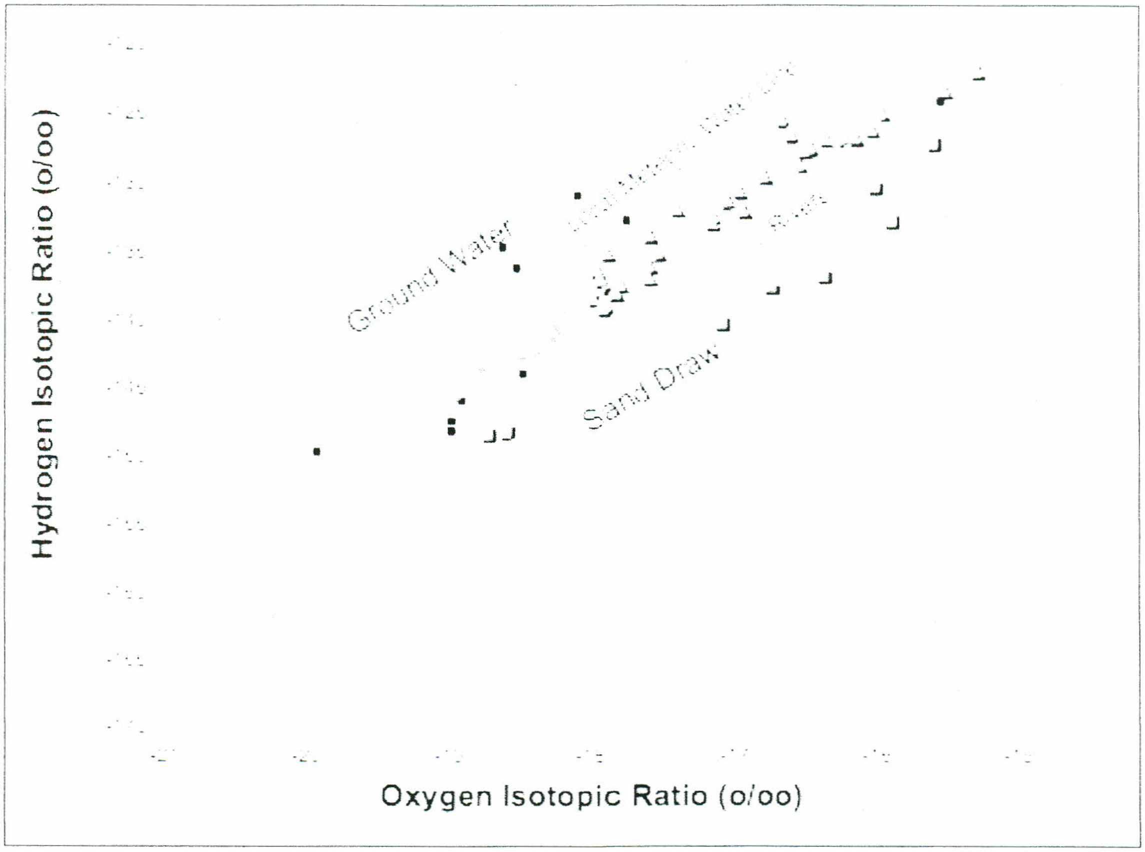

Hydrogen Isotopic Ratio (o/oo)
Oxygen Isotopic Ratio (o/oo)
Ground Water
Sand Draw

Table 1

Well Name	Date	Depth of well (ft)	Water Elevation (ft)
R-4	06/01/09	21.3	dry
R-5	"	52.4	dry
R-5D	"	73.1	dry
R-6	"	53	5384.1
R-7	"	51.7	5448.2
R-8	"	51.9	5481.6
R-9	"	52.1	5469.7
R-9D	"	67.1	5462.8
R-10	"	51	5443
R-11	"	51.5	5442.9
R-12	"	51.7	5455.1
R-13	06/29/09	52.7	5440
R-13D	"	73.2	5424
R-14D	"	49.3	5479.4
R-14S	"	22.2	dry
R-15D	"	55.7	dry
R-15S	"	30.6	dyr
R-16D	"	63.7	5466.2
R-16S	"	28.7	dry
R-18	"	53.3	5482.3
R-19	"	91.8	5390.4
R-20	"	57.3	5448.4
R-21	"	137.7	5345.9
R-22	"	123.3	5365.9

Table 2

Table 2

Well	Depth (ft)	Water Elevation (ft)	Bicarbonate (mg/L)	Chloride (mg/L)	Sulfate (mg/L)	Calcium (mg/L)	Magnesium (mg/L)	Potassium (mg/L)	Sodium (mg/L)
[illegible] 10	60	5443	260	4.0	12[illegible]	8.1	1.6	1.1	173
[illegible] 11	60	5434	184	4.0	110	6.2	1.5	1.0	106
[illegible] 12	60	5432	37	54.0	1[illegible]	114.0	2.6	3.[illegible]	[illegible]61
[illegible] 15	52	54[illegible]0	172	13.0	653	126.0	1.6	2.6	214
[illegible] 20	55	5440	151	17.0	4[illegible]00	399.0	37.1	5.0	1620
[illegible]	60	5446	158	17.0	[illegible]600	58.5	6.1	2.7	605
[illegible] 8	60	5478	80	164.0	2030	370.0	24.6	1.3	553
[illegible] 10	60	5460	530	37.0	632	170.0	11.0	2.7	303
Wash well	>200	na	200	14.0	310	6.7	nd	nd	201
Well	Iron (mg/L)	Specific Conductance (uMhos/cm)	pH (units)	Total Dissolved Solids (mg/L)	[illegible]O (parts per thousand VSMOW)	[illegible]D (parts per thousand VSMOW)	Tritium	Carbon 14 Conventional Age	[illegible]C (parts per thousand PDB)
[illegible] 10	1.2	814	8.4	516	[illegible]	[illegible]	<0.5	na	na
[illegible] 11	nd	533	8.5	352	[illegible]	[illegible]	[illegible]	na	na
[illegible] 12	nd	3850	8.2	2950	[illegible]	[illegible]	<0.5	[illegible]50	21.1
[illegible] 15	nd	1260	[illegible]	1070	[illegible]	[illegible]	<0.5	17150	[illegible]
[illegible] 20	nd	[illegible]810	[illegible]6	6200	[illegible]	[illegible]	[illegible]	na	na
[illegible]	nd	3100	8.0	2300	[illegible]	[illegible]	2.2	na	na
[illegible] 8	nd	4120	[illegible]	3320	[illegible]	[illegible]	[illegible]	na	na
[illegible] 10	nd	2320	[illegible]	632	[illegible]	[illegible]	<0.5	22150	10.5
Wash well	0.1	1150	8.8	821	[illegible]	[illegible]	<0.5	8020	11.1