ARCADIS

Appendix C-3

Stable Isotope Study

ARCADIS
630 Plaza Drive
Suite 200
Highlands Ranch
Colorado 80129
Tel 720.344.3500
Fax 720.344.3535

MEMO

To:
File

Copies:

From:
Magnus Skold

Date:
6 July 2009

ARCADIS Project No.:
GP08WSMR.0REP.DP001

Subject:
Use of Stable Isotope Composition to Estimate Infiltration Rate at the HELSTF

Introduction

Discharge of wastewater, leakage from corroded piping associated with potable water supply and sanitary systems, and leakage from the Sanitary Treatment System have resulted in the creation of a partial saturation of the vadose zone above the Regional Aquifer at the High Energy Laser Systems Test Facility (HELSTF). The partially saturated vadose zone does not sustain meaningful extraction of water and impacted water from the vadose zone soil water will therefore not be used for drinking water. However, infiltration through the vadose zone may result in impacts to the Regional Aquifer. The infiltration rate is unknown but is important because it controls the mass loading of contaminants to the Regional Aquifer. The stable isotopic signatures of the infiltrating water and of groundwater in the Regional Aquifer were used to estimate infiltration rate to the Regional Aquifer in order to support evaluation of contaminant mass loading to the Regional Aquifer.

Water samples were collected from the HELSTF water source, the Regional Aquifer upgradient and downgradient of the HELSTF, and from the vadose zone at the HELSTF. The goals of the study are to investigate the isotopic composition of the three sample groups to assess any difference in isotopic composition and to estimate the rate of infiltration from the vadose zone to the Regional Aquifer. The isotopic composition of the samples is discussed below and the infiltration rate is estimated based on differences in isotopic signature.

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Sample Collection

A total of 23 aqueous samples were collected from monitor wells within and near the HELSTF and were analyzed for stable isotope ratios of oxygen and hydrogen ($^{18}O/^{16}O$ and $^{2}H/^{1}H$). The samples were collected to assess the isotopic composition of the water source, infiltrating water, upgradient portion of the Regional Aquifer, and the downgradient portion of the Regional Aquifer.

1. Two samples were collected from the HELSTF water source. One sample was collected from MAR-3 and a tap water sample was collected from the Laser Systems Test Center (LSTC) building.

2. Twelve samples, including two duplicates, were collected from monitor wells installed in the vadose zone at the HELSTF.

3. Four samples were collected from the Regional Aquifer in the upgradient portion of the HELSTF.

4. Five samples were collected from the Regional Aquifer in the downgradient portion of the HELSTF.

The sampling locations are displayed on **Figure 1** and the analytical results are presented in **Table 1**. Most of the samples (18) were collected during the March-April 2009 sampling event and were analyzed at one occasion. The samples were either collected as grab samples using a bailer or purged using a pump. Four additional samples, including two duplicates, were collected on June 3, 2009, and were analyzed on a separate occasion.

Sample Analysis

The samples were analyzed at the Stable Isotope Facility and the University of California at Davis. The results of the analysis are presented as a relative difference in isotopic ratio between the samples and world standard[1]. The relative isotopic ratio, expressed in units of per mil (per thousandth, or ‰), for oxygen is:

$$\delta O^{18} = \frac{\left(\frac{^{18}O}{^{16}O}\right)_{sample} - \left(\frac{^{18}O}{^{16}O}\right)_{s\tan dard}}{\left(\frac{^{18}O}{^{16}O}\right)_{s\tan dard}} \cdot 1000$$

[1] Appelo, C.A.J., and D. Postma. 2005. Geochemistry, groundwater and pollution, 2nd Edition. A.A. Balkema Publishers. London.

and similarly for deuterium (^{2}H, or D) and hydrogen (^{1}H, or simply H):

$$\delta D = \frac{\left(\frac{D}{H}\right)_{sample} - \left(\frac{D}{H}\right)_{s\tan dard}}{\left(\frac{D}{H}\right)_{s\tan dard}} \cdot 1000$$

Water samples lighter than the world standards have negative isotope ratios (• ^{18}O and • D) while samples enriched in heavier isotopes compared to the world standards have positive values. Within a set of samples, samples with more positive, or less negative, relative isotope ratios are enriched in heavier water compared to samples with lower ratios.

The analytical uncertainty at the Stable Isotope Facility is approximately 0.2 per mil for • ^{18}O and approximately 0.5-0.6 for • D. Heavier and lighter standards are analyzed with the samples to bracket the relative isotopic ratios. The result of one duplicate sample (HMW-21) was similar to the sample collected during the first sampling event. The second duplicate sample (DRW-2) was flagged as uncertain by the laboratory. The sample collected at DRW-17 was also reported as uncertain by the laboratory. These two uncertain results are excluded from this analysis but are presented in **Table 1**.

Data Interpretation

The results of the isotopic analysis are presented on **Figure 2**. The samples collected from the current HELSTF water source (MAR-3 and LSTC tap water) have similar isotopic composition and have the lightest isotopic composition among all analyzed samples. No physicochemical processes are expected to occur between MAR-3 and the LSTC building and the samples are expected to have similar isotopic signature. These samples have the lightest isotopic signature because they have not been exposed to evaporation. Water molecules with lighter isotope signature evaporate preferentially compared to water molecules with heavier signature, leaving behind selectively heavier water. Thus, the isotopic signature of the water source alters when discharged and the signature of the samples collected at MAR-3 and the LSTC building are not representative of the isotopic signature of the infiltrating water.

The samples collected from the vadose zone show a relatively large spread in isotopic composition. The samples collected near the Sanitary Treatment System (HMW-01, DRW-10, HMW-40, and HMW-43) have heavier isotopic composition than most of the other samples collected from the vadose zone. This is not unexpected as water contained in the Sanitary Treatment System for long periods of time would have been enriched in heavier isotopes due to evaporation.

The Regional Aquifer contains water originating from another source than the soil water in the vadose zone and has a different, generally lighter, isotopic signature. Samples collected from the upgradient portion of the Regional Aquifer have lighter isotopic signature compared to the samples collected from wells installed in the downgradient portion of the Regional Aquifer. Mixing of heavier infiltrating soil water with upgradient regional groundwater results in a change in relative isotopic ratio. The mixing ratio is calculated based on average isotopic signatures of the three groups of water samples and is discussed below.

Calculation of Infiltration Ratio

The relative isotopic ratios are conservative during mixing of water sources and can be calculated from the flow rates and relative isotopic signatures of the mixing water. At the HELSTF, the hydrogen and oxygen isotopic composition of the groundwater in the downgradient portion of the Regional Aquifer is a result of regional upgradient groundwater mixing with infiltrating soil water:

$$\partial_{RD} = \partial_{RU} \cdot \frac{Q_R}{Q_R + Q_{\inf}} + \partial_{\inf} \cdot \frac{Q_{\inf}}{Q_R + Q_{\inf}}$$

Where subscript *RU* represents upgradient regional water, *RD* downgradient regional water, inf represents infiltrating soil water, and flow rate is represented by the letter *Q*. The mixing equation is valid for both ^{18}O and D isotope ratios.

The equation can be re-arranged to calculate the ratio of the infiltration rate to ambient groundwater flow (subsequently termed the infiltration ratio):

$$\frac{Q_{\inf}}{Q_{RU}} = \frac{(\partial_{RD} - \partial_{RU})}{(\partial_{\inf} - \partial_{RU})}$$

The infiltration ratio was calculated based on all isotope samples excluding samples flagged as uncertain by the laboratory (DRW-17 and DRW-2). In the calculations, average values for two groups were used while each measurement was used individually of the third group to calculate a distribution of mixing ratios. The samples collected from the upgradient and downgradient portion of the Regional Aquifer have limited spread in measured relative isotopic ratios and the average oxygen and hydrogen relative isotope ratios were used in the calculations (**Table 2**). Because of the wider distribution of relative isotopic ratios of samples collected from the vadose zone, each individual value was used to calculate a distribution of mixing ratios. A mixing ratio close to zero indicates insignificant infiltration relative to lateral groundwater flow while large mixing ratios indicate that significant infiltration takes place. The results of the calculated mixing ratio for each sample are presented on **Figure 3**. The calculated mixing ratios vary and some

values are negative; a result of individual samples collected from the vadose zone being lighter than the average upgradient groundwater sample. However, the majority of the values are positive (confirming infiltration and mixing): the average calculated infiltration ratio is 0.24 based on hydrogen isotopes and 0.42 based on the oxygen isotopes. The range in calculated mixing ratio indicates some uncertainty in the analysis but indicates that on average every gallon of infiltrating water mixes with 2.4 to 4.2 gallons of laterally flowing regional groundwater.

The calculated infiltration ratio and lateral groundwater flow in the Regional Aquifer were used to estimate the infiltration rate at the HELSTF. The groundwater flow was calculated based on Darcy's law, the thickness of the Regional Aquifer, and the width of the HELSTF area where infiltration occurs.

$$Q_{RU} = -K \cdot \frac{dh}{dl} \cdot A$$

Q_{RU} represents the lateral groundwater flowing beneath the HELSTF, K is the hydraulic conductivity (ft/day), dh/dl is the hydraulic gradient (ft/ft), and A is the cross-sectional area calculated as the product of the thickness, b, of the Regional Aquifer and the width, W, of the HELSTF perpendicular to groundwater flow:

$$A = b \cdot W$$

The following parameter values were used to calculate the lateral groundwater flow:

- The hydraulic conductivity was assumed to be 5.2 feet per day based on a previous pumping test;
- The hydraulic gradient was estimated to be 0.0027 foot per foot based on water levels measured in January 2009;
- The thickness of the Regional Aquifer is approximately 30 feet at the HELSTF; and
- The width of the HELSTF perpendicular to the groundwater flow direction is approximately 1,500 feet.

The parameters presented above result in a lateral groundwater flow of 3.3 gallons per minute (420 cubic feet per year or 0.29 cubic foot per minute). Based on mixing ratio ranging from 0.24 to 0.42, the resulting infiltration rate is calculated to approximately 0.8 to 1.4 gallons per minute. A summary of the water balance at the HELSTF (Appendix C-3) indicates a greater flux of water from leaking piping, leaking ponds, and sewage discharge to the immediate subsurface (>~~5~~ 2 gallons per minute). However, some water that infiltrates to the shallow subsurface is expected to be transported to the surface by capillary forces and evaporate (the evapotranspiration extinction depth is estimated to be greater than 15 feet at the

Form

site). The samples for this stable isotope study, however, were collected from the vadose zone at depths below the evapotranspiration extinction depth and from the Regional Aquifer, and the analysis represents flux from the vadose zone to the Regional Aquifer. Consequently, it inherently accounts for any water losses dues to evaporation from shallow soils and would therefore be expected to yield slightly lower estimates of the infiltration rate than the water balance analysis.

Conclusions

- Soil water in the vadose zone has a heavier isotopic signature than water from the Regional Aquifer as expected by enrichment of heavier water molecules during evaporation;

- The infiltration ratio, expressed as the ratio of infiltrating water flow to lateral groundwater flow, was calculated to approximately 0.24 to 0.42 based on stable isotope composition of samples from the vadose zone and Regional Aquifer at the HELSTF; and

- Based on a lateral groundwater flow of 3.3 gallons per minute beneath the HELSTF, the infiltration (recharge) rate to the Regional Aquifer was calculated to 0.8 to 1.4 gallons per minute.

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Table 1. Results of Oxygen and Hydrogen Isotope Analysis.

Sample ID	δD [per mil]	δ ^{18}O [per mil]	SWMU	Sampling Location	Sampling Date
Source Water					
HELSF-DRWT-MAR-003-0609	-64.87	-9.6	MAR 3 well	MAR 3 Well	6/3/2009
HELSF-DRWT-LSTC-001-0609	-65	-9.12	LSTC tap water	LSTC tap water	6/3/2009
Vadose Zone Wells					
HLSF-0148-DRW-010-0309	-44.19	-4.38	148	DRW-10	3/19/2009
HLSF-0154-DRW-012-0409	-47.53	-5.05	154	DRW-12	4/7/2009
HLSF-0154-DRW-002-0409	*-47.58*	*-6.96*	*154*	*DRW-2*	*4/9/2009*
HLSF-0154-DRW-007-0409	-44.41	-5.47	154	DRW-7	4/15/2009
HLSF-3839-HMW-033-0309	-49.02	-5.42	38 and 39	HMW-33	3/18/2009
HLSF-0143-HMW-043-0309	-39.93	-5.18	143	HMW-43	3/30/2009
HLSF-0143-HMW-001-0409	-42.24	-5.06	143	HMW-1	4/2/2009
HLSF-0143-HMW-040-0409	-32.08	-3.72	143	HMW-40	4/17/2009
HLSF-0144-HMW-021-409	-58.6	-7.66	144	HMW-21	4/15/2009
HELSF-0146-HMW-021-0609	-57.96	-7.68	146	HMW-21	6/3/2009
HELSF-0154-DRW-002-0609	-45.44	-6.46	154	DRW-2	6/3/2009
HLSF-0148-HMW-010-0309	-49.79	-5.71	148	HMW-12	3/14/2009
Downgradient Regional Wells					
HLSF-0148-DMW-014-0309	-45.21	-5.05	148	DRW-14	3/19/2009
HLSF-0144-HMW-056-0409	-45.91	-5.3	144	HMW-56	4/15/2009
HLSF-0085-HMW-606-0309	-47.04	-4.98	85	HMW-60	3/4/2009
HLSF-0085-HMW-062-0309	-47.9	-5.64	85	HMW-62	3/4/2009
HLSF-0085-HMW-063-0309	-47.87	-5.19	85	HMW-63	3/5/2009
Upgradient Regional Wells					
HLSF-0154-DRW-016-0309	-48.3	-5.35	154	DRW-16	3/9/2009
HLSF-3839-HMW-034-0309	-48.16	-5.23	38 and 39	HMW-34	3/11/2009
HLSF-0085-HMW-061-0309	-49.05	-5.71	85	HMW-61	3/4/2009
HELSF-0154-DRW-017-0609	*-45.74*	*-5*	*154*	*DRW-17*	*6/3/2009*

Note: Samples collected at DRW-2 on 4/9/2009 and DRW-17 on 6/3/2009 were flagged as uncertain by the laboratory because of too high standard deviation of triplicate analysis.

LSTC - Laser Systems Test Center.

SWMU - Solid Waste Management Unit.

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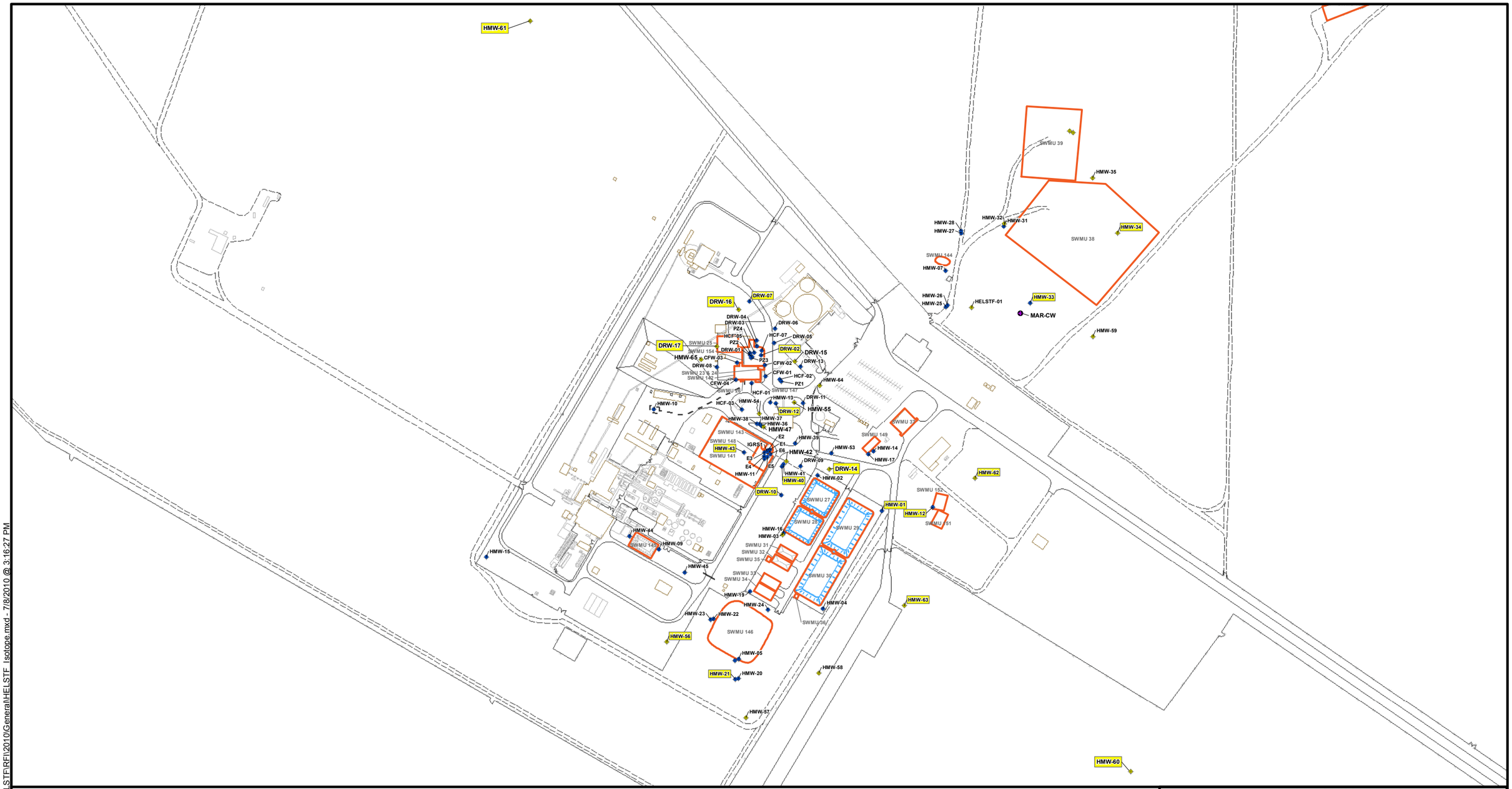
Table 2. Average Isotopic Ratios in Soil Water and Groundwater Samples from HELSTF.

Sample Group	All Samples		Excluding Outliers	
	δD [per mil]	δ ^{18}O [per mil]	δD [per mil]	δ ^{18}O [per mil]
Regional Aquifer - Upgradient	-47.81	-5.32	-48.50	-5.43
Regional Aquifer - Downgradient	-46.79	-5.23	-46.79	-5.23

HELSTF - High Energy Laser Systems Test Facility.



LEGEND

- WELLS SCREENED IN THE VADOSE ZONE
- WELLS SCREENED IN THE REGIONAL AQUIFER
- WATER SUPPLY WELLS
- SWMU BOUNDARY
- SITE FEATURES
- BUILDING
- POND/LAGOON
- FENCE
- FORMER UST AND FUEL LINE
- RAIL ROAD
- PAVED ROAD
- DIRT ROAD
- HMW-60 ISOTOPE SAMPLING LOCATIONS

N

0 190 380 760 Feet

WHITE SANDS MISSILE RANGE
NEW MEXICO
REVISED PHASE III RCRA FACILITY INVESTIGATION (RFI) REPORT – HELSTF SITE – SECOND REVISION (AUGUST, 2010)

HELSTF
ISOTOPE SAMPLING LOCATIONS

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FIGURE
1

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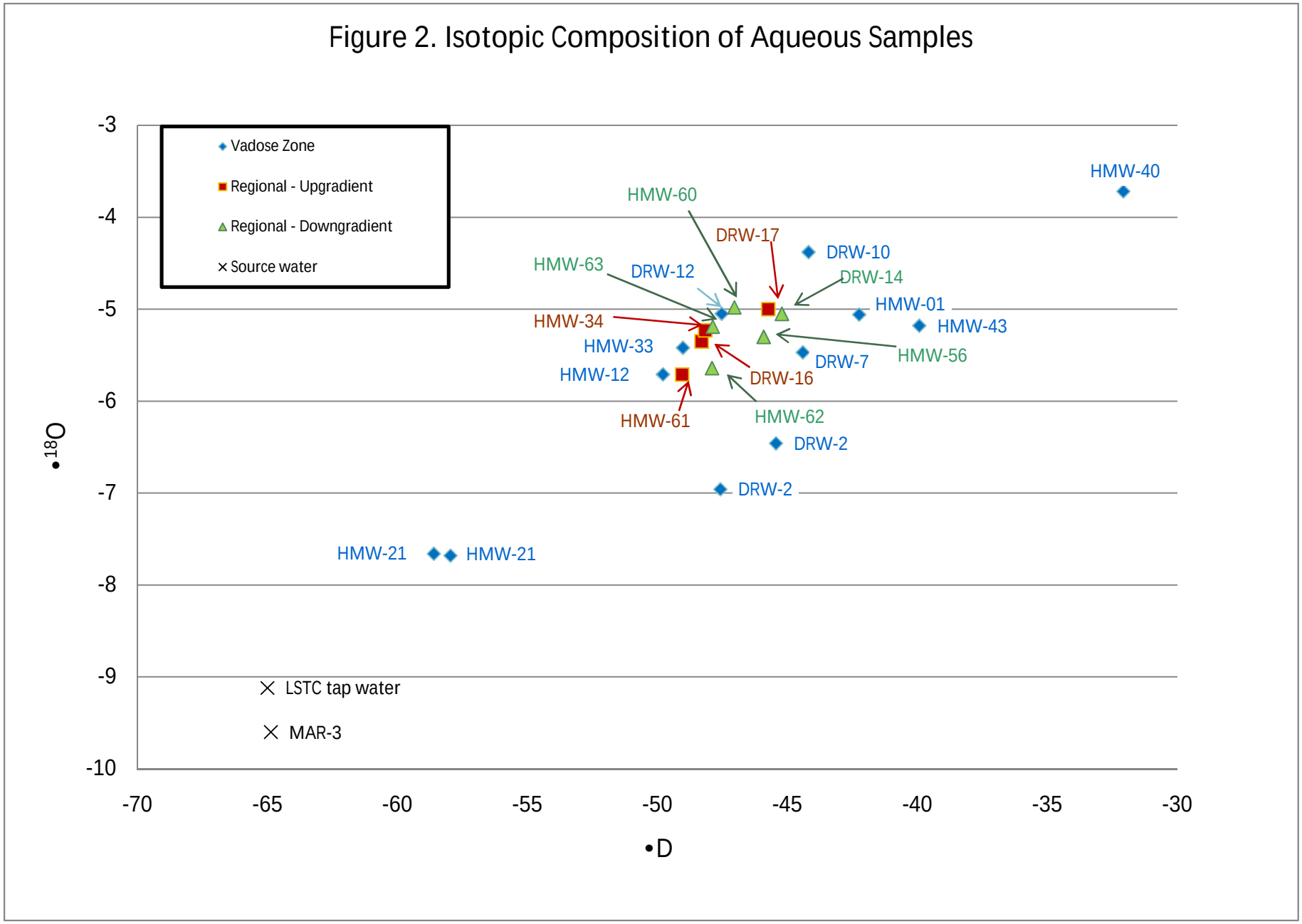
Figure 2. Isotopic Composition of Aqueous Samples
Vadose Zone
Regional - Upgradient
Regional - Downgradient
Source water
HMW-40
HMW-60
DRW-17
DRW-10
HMW-63
DRW-12
DRW-14
HMW-01
HMW-34
HMW-43
HMW-33
HMW-56
DRW-7
HMW-12
DRW-16
HMW-61
HMW-62
DRW-2
DRW-2
HMW-21
HMW-21
LSTC tap water
MAR-3
-3
-4
-5
-6
-7
-8
-9
-10
•18O
-70
-65
-60
-55
-50
-45
-40
-35
-30
•D

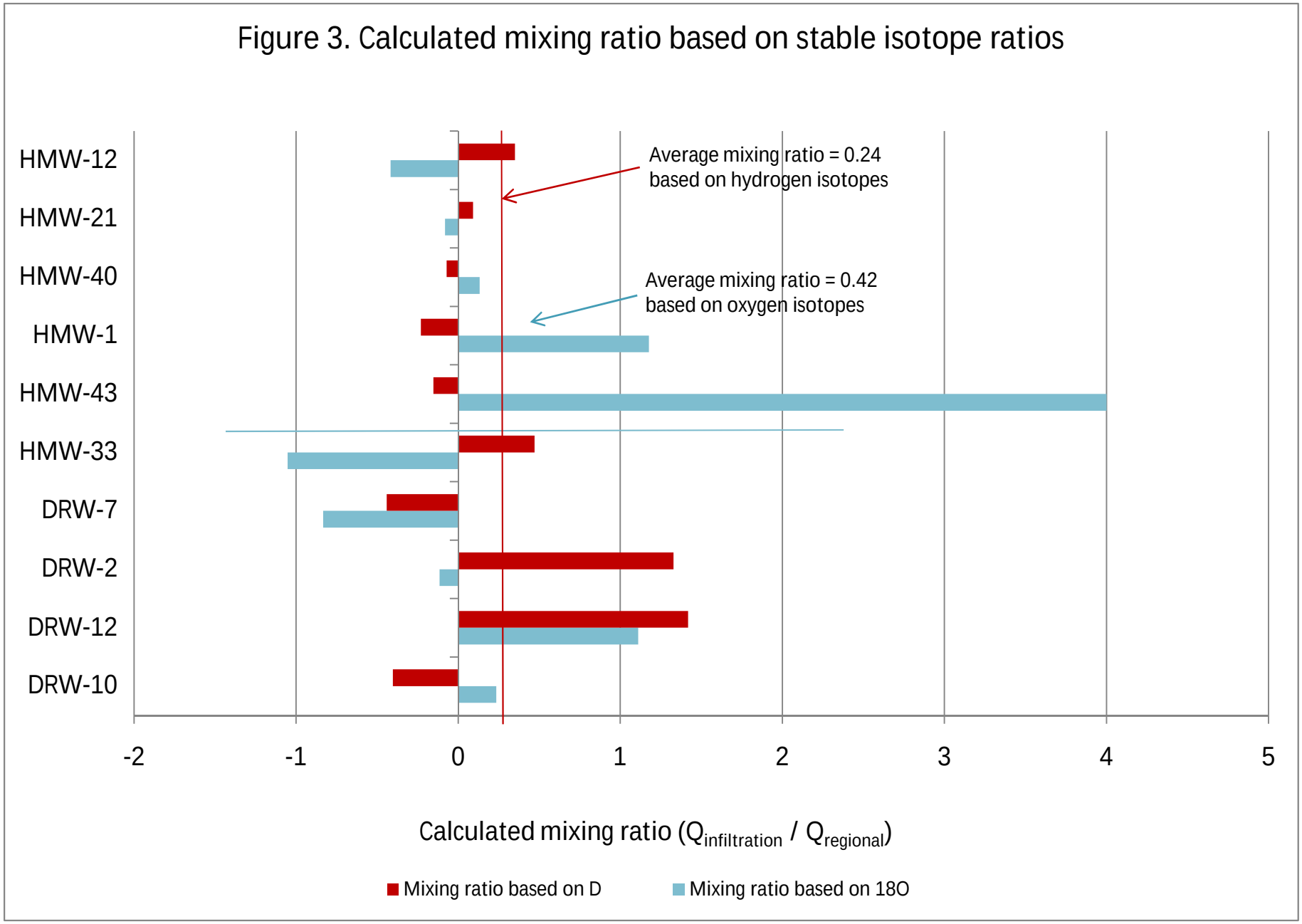
Figure 3. Calculated mixing ratio based on stable isotope ratios
HMW-12
HMW-21
HMW-40
HMW-1
HMW-43
HMW-33
DRW-7
DRW-2
DRW-12
DRW-10
Average mixing ratio = 0.24
based on hydrogen isotopes
Average mixing ratio = 0.42
based on oxygen isotopes
-2
-1
0
1
2
3
4
5
Calculated mixing ratio ($Q_{infiltration}$ / $Q_{regional}$)
Mixing ratio based on D
Mixing ratio based on 18O