



TECHNICAL MEMORANDUM

To: Eva Blumenstein and James Jensen PE, Maui Department of Water Supply
From: Elanor Heil, PhD and Kevin Gooding CPG, INTERA Incorporated
Date: May 6, 2026
Re: Reanalysis of Ha'ikū and Honopou Aquifer System stable isotope and geochemistry data

1.0 Executive Summary

This technical memorandum presents a reanalysis of stable isotope ($\delta^{18}\text{O}$, $\delta^2\text{H}$) and major ion geochemistry data collected by Bees (2024) in the Ha'ikū and Huelo area of northeast Maui. The central questions are whether the Ha'ikū basal aquifer is geochemically distinct from the overlying perched aquifer and surface water system, and whether the geochemical evidence is consistent with basal groundwater discharging to coastal groundwater-dependent ecosystems (GDEs) at Maliko Gulch, Peahi, Hōolawa, and Kū'ike. The analysis draws on the isotope and major ion datasets from Bees (2024), to which geographic coordinates have been added to enable spatial analysis not conducted in the original thesis.

Bees (2024) concluded, based on unpaired t-tests, that groundwater and surface water in Ha'ikū are statistically distinct in both stable isotopes and major ion chemistry, and that this distinction is absent in Huelo. This reanalysis by INTERA agrees with that finding and replicates the key statistical results using a consistent spatial subsetting approach and an expanded analytical framework. The isotope separation in Ha'ikū is confirmed here with stronger statistics ($\delta^{18}\text{O}$ $t = -8.7$, $p < 10^{-6}$ versus Bees' $p = 8.1 \times 10^{-5}$), attributable to applying the test to a spatially defined Ha'ikū-only subset rather than the full dataset. The ion chemistry separation is also replicated across all seven major ions tested. This reanalysis additionally extends the Bees (2024) findings by applying Cl/Na and Br/Cl ratio analysis, a two end-member mixing model for the Maliko Gulch coastal zone, and a formal comparison of temporal isotope variability between wells and surface waters. Bees (2024) tentatively attributed elevated chloride in coastal wells to saltwater intrusion. The Cl/Na ratios in high-Cl wells (mean 1.62, approaching but below the seawater value of 1.81) and the Br/Cl ratios (mean 0.0038, near the seawater value of 0.0034) are consistent with rock-water interaction in marine-influenced Honomānū Basalt, though they do not rule out a saltwater intrusion component.

The principal findings are: (1) major ion chemistry is the most direct line of evidence for geochemical distinction between basal wells and surface waters, with all seven ions significantly different ($p < 0.01$) and well chloride averaging nine times higher than streams; (2) stable isotopes in Ha'ikū show a statistically significant difference in recharge signatures between wells and surface waters, consistent with the ion chemistry finding; (3) well isotope values are stable over a 20-month record while stream values fluctuate seasonally, which is consistent with an isolated reservoir; and (4) an initial assessment using a two end-member mixing model at Maliko Gulch indicates that coastal well chemistry is broadly consistent with a mixture of basal and surface water, though this assessment is preliminary and should not be treated as a precise flux estimate without direct estuary sampling.

2.0 Background and Study Context

The study area occupies the northeastern flank of Haleakalā, a shield volcano on the island of Maui. Three volcanic series underlie the region and control its hydrogeology; from oldest to youngest, these are the Honomānū Basalt, the Kula Volcanics, and the Hāna Volcanics (Stearns and MacDonald, 1942). Each represents a distinct eruptive period, and the time intervals between them allowed weathered surfaces and thick paleosol layers to develop at the contacts.

The Honomānū Basalt is the oldest and deepest unit, forming the foundation of the shield volcano. It has relatively high hydraulic conductivity and hosts the basal freshwater lens, a body of freshwater that floats on the underlying saltwater in accordance with the Ghyben-Herzberg principle (Gingerich, 1999a). The Honomānū Basalt outcrops only near the coastline and in the floors of deeply eroded gulches such as Maliko Gulch, where it is exposed by erosion through the overlying Kula Volcanics (Stearns and MacDonald, 1942). Streams flowing over Honomānū Basalt typically lose water to the permeable subsurface before reaching the coast, in contrast to streams over the Kula Volcanics, which generally reach the ocean (Scholl et al., 2002).

The Kula Volcanics erupted after the Honomānū series and now cover much of northeast Maui's surface, nearly blanketing the underlying Honomānū Basalt (Langenheim and Clague, 1987). The Kula Volcanics are hypothesized to be less permeable than the Honomānū Basalt, owing to a higher density of silica sheets within the rock structure (Stearns and McDonald, 1942), and are associated with perched groundwater bodies that sit above the regional basal water table. Because a sufficiently long interval separated the Honomānū and Kula eruptive periods, extensive weathering produced a paleosol layer at their contact. Gingerich (1999b) hypothesized that this paleosol aquitard resists vertical flow, creating a saturated perched zone within the Kula Volcanics above an unsaturated zone in the uppermost portion of the underlying Honomānū Basalt. If the aquitard is continuous and effective in Ha'ikū, it would physically separate stream-fed perched recharge from the underlying basal aquifer. Meyer (2000) contested this view for the more easterly Nāhiku area, where he proposed that all three volcanic units may be fully saturated and more directly connected, a difference possibly attributable to higher rainfall or lateral geological heterogeneity in that sub-region.

The Hāna Volcanics are the youngest unit, occupying a small portion of the eastern study area. They are thin, highly permeable, and of limited areal extent (Gingerich, 1999a). Their high permeability means they contribute little resistance to vertical flow and are not considered a significant aquitard.

Perched groundwater within the Kula Volcanics was considered by Niu et al. (2020) to be a young, relatively rapidly recharged water body and not a viable long-term water supply source. Surface waters, including streams and springs in the study area, are understood to be fed largely by perched aquifer baseflow and direct precipitation runoff rather than by the basal lens. Niu et al. (2017) found, using noble gas tracers across northeast Maui from Ha'ikū to Nāhiku, that the basal and perched aquifer systems show distinct geochemical signatures and that basal wells do not exhibit the temporal isotopic variability associated with recent precipitation recharge. The geochemical evidence evaluated in this reanalysis either supports or qualifies the physical separation hypothesis proposed by Gingerich (1999b) for the Ha'ikū area specifically.

The Bees (2024) thesis is the most current geochemical dataset for the Ha'ikū and Huelo region. This reanalysis of the data collected for Bees (2024) applies independent statistical methods, full spatial analysis of both datasets, and mixing model calculations targeted at the GDE connectivity question.

3.0 Dataset Summary

This reanalysis draws on the stable isotope and major ion datasets from Bees (2024). The isotope dataset contains 168 samples (80 precipitation, 41 stream, 35 well, and 12 spring) collected from November 2022 through July 2024 (**Table 1**). The major ion dataset contains 26 samples (13 well, 7 spring, and 6 stream), with concentrations of thirteen ions including chloride, sodium, magnesium, sulfate, calcium, potassium, and bromide (**Table 2**). Geographic coordinates were added to both datasets to enable the spatial analyses presented in this section; all geochemical values are as reported in the Bees (2024) appendix without modification.

Stable isotopes of hydrogen ($\delta^2\text{H}$) and oxygen ($\delta^{18}\text{O}$) are natural tracers that record the elevation and pathway of precipitation before it enters the ground. As moist air rises over Haleakalā, precipitation becomes progressively depleted in the heavier isotopes because the heavier molecules condense and fall first, leaving the remaining moisture lighter with increasing altitude. Water that recharges a deep aquifer at high elevation therefore carries a more negative isotopic signature than water infiltrating near the coast. A systematic difference between well values and stream or spring values is therefore evidence that water originated at different elevations or followed different flow paths. Separately, isotope values that remain stable over time while surface waters fluctuate with seasonal rainfall suggest a large, isolated subsurface reservoir rather than a system in close hydraulic communication with surface water.

Deuterium excess (d-excess) is calculated as $d = \delta^2\text{H} - 8 \times \delta^{18}\text{O}$ and provides a measure of the degree to which a water sample has been affected by evaporation after it condensed as precipitation. Global average precipitation has a d-excess of approximately 10‰ (per mille or parts per thousand), reflecting the kinetic fractionation conditions typical of ocean evaporation (Craig, 1961). Values substantially below 10‰ indicate post-condensation evaporation, which fractionates the isotopes along a sub-meteoric slope and reduces d-excess.

Major ion chemistry provides a more direct and mechanistically independent line of evidence. As groundwater circulates slowly through volcanic rock, it dissolves minerals and accumulates a characteristic ion load. Basal groundwater in the Honomānū Basalt, which retains residual marine-influenced salts from its depositional history, develops elevated concentrations of chloride and sodium that cannot be attributed to elevation-differentiated precipitation alone. The Cl/Na mass ratio approaches the seawater value (1.81) in water that has interacted with marine-influenced rock, while the Br/Cl ratio near the seawater value (0.0034) confirms a marine chloride source rather than simple saltwater dilution (Davis et al., 1998). Perched water, which has circulated only through the shallower Kula Volcanics for a shorter residence time, retains a lower ion load and a different ion ratio signature. Springs with inverted Na/Cl ratios (where sodium exceeds chloride) could reflect weathering of basalt, a common signature in young volcanic groundwater (Hem, 1985; Scholl et al., 1996).

Table 1. Isotope summary statistics by sample type ($\delta^{18}\text{O}$, $\delta^2\text{H}$, and deuterium excess).

Type	n	Mean $\delta^{18}\text{O}$ (‰)	Std $\delta^{18}\text{O}$	Mean $\delta^2\text{H}$ (‰)	Std $\delta^2\text{H}$	Deuterium-excess (‰)
Precipitation	80	-2.59	± 1.41	-6.72	± 12.07	13.98
Stream	41	-2.92	± 0.71	-7.59	± 5.75	15.80
Spring	12	-2.69	± 0.11	-6.24	± 1.00	15.29
Well	35	-3.05	± 0.44	-9.28	± 2.73	15.13

Table 2. Major ion mean and standard deviation by sample type.

Ion	Well Mean \pm SD (mg/L)	Stream Mean \pm SD (mg/L)	Spring Mean \pm SD (mg/L)	Ratio Well:Stream
Chloride	128.2 \pm 91.2	14.0 \pm 5.5	20.1 \pm 9.7	9.2 \times
Sodium	77.4 \pm 52.2	9.9 \pm 3.7	26.1 \pm 26.2	7.8 \times
Magnesium	13.0 \pm 7.0	2.4 \pm 0.8	2.6 \pm 0.9	5.4 \times
Sulfate	20.9 \pm 14.5	3.8 \pm 1.5	9.8 \pm 9.1	5.5 \times
Calcium	14.2 \pm 6.2	2.3 \pm 0.6	3.0 \pm 1.1	6.2 \times
Potassium	4.8 \pm 2.5	1.0 \pm 0.4	1.5 \pm 1.0	4.8 \times
Bromide	0.45 \pm 0.35	0.09 \pm 0.04	0.13 \pm 0.15	5.0 \times

SD = Standard Deviation, mg/L = milligrams per liter

4.0 Evidence for Basal/Perched Aquifer Separation

The question of whether the Ha'ikū basal aquifer is geochemically distinct from the perched system and surface waters is addressed using three lines of evidence: major ion chemistry, stable isotopes in Ha'ikū, and temporal isotope stability. Each is grounded in a different physical mechanism and has known limitations. No single line is conclusive on its own; the value of the analysis lies in whether they are consistent with one another.

Bees (2024) reached similar conclusions using unpaired t-tests on isotopes by region and on major ions across the full dataset. This reanalysis replicates those results and extends them with a different, finer spatial subsetting approach, per-sample ion ratio analysis, a temporal stability comparison, and a mixing model for the Maliko Gulch coastal zone.

4.1 Line 1: Major Ion Chemistry

Major ion concentrations were measured in 26 samples and compared between the well group (n = 13) and the combined surface water group (streams and springs, n = 13) using unpaired two-sample t-tests.

An unpaired t-test is appropriate here because the two groups are independent, they represent water from different sources, and no assumption of equal variance is made (Welch correction applied). The null hypothesis for each ion is that wells and surface waters are drawn from populations with the same mean concentration. The t-statistic measures how many standard errors the group means are apart; the p-value gives the probability of observing that difference by chance if the null hypothesis were true. All seven ions tested are significantly different between wells and surface waters ($p < 0.01$; **Table 3**). This result agrees with Bees (2024), who found the same pattern for chloride, bromide, sulfate, magnesium, and calcium (but did not test sodium and potassium in the same framework). This reanalysis additionally finds that sodium ($p = 0.002$) and potassium ($p = 0.001$) are significantly different, consistent with the broader ion enrichment pattern.

Table 3. Major ion t-test results: wells vs. streams and springs (Welch unpaired t-test)

Ion	t-statistic	p-value	Significant?	Well:Stream Ratio
Chloride	4.4	0.0002	Yes	9.2×
Sodium	3.8	0.0009	Yes	7.8×
Magnesium	5.4	0.00002	Yes	5.4×
Calcium	5.8	0.00001	Yes	6.2×
Sulfate	3.1	0.005	Yes	5.5×
Bromide	3.6	0.0015	Yes	5.0×
Potassium	4.2	0.0003	Yes	4.8×

The magnitude of the difference is large: mean well chloride is 128 milligrams per liter (mg/L) (range 8–281 mg/L) compared to 14 mg/L (range 7–24 mg/L) for streams and 20 mg/L (range 8–36 mg/L) for springs. The well range spans more than two orders of magnitude, reflecting hydrogeologic variability among the wells. Three wells (Well-3, Well-9, Well-13) have chloride below 50 mg/L, within the range of some springs, which may indicate perched or mixed water sources for those specific wells. The eight wells with chloride above 100 mg/L all cluster in the northern coastal band (latitude $\geq 20.93^\circ\text{N}$), which is consistent with the geographic distribution and consistent with basal groundwater discharging toward the coast (**Figure 1**).

Ion ratios provide further chemical fingerprinting. The Cl/Na ratio reflects whether a sample's chemistry is dominated by marine-derived ions (seawater Cl/Na = 1.81) or by freshwater rock-water interaction (lower ratios). The Br/Cl ratio distinguishes marine-origin chloride (seawater Br/Cl = 0.0034) from chloride derived from volcanic soil or organic matter decomposition (elevated Br/Cl; Davis et al., 1998). **Table 4** shows per-sample Cl/Na and Br/Cl ratios for all samples. Well Cl/Na ranges from 1.26 to 1.84 (mean 1.62), approaching seawater (1.81) for the high-Cl coastal wells (**Figure 2**). Well Br/Cl ranges from 0.0002 to 0.0048 (mean 0.0038), close to the seawater value of 0.0034 for most wells. Stream Br/Cl is consistently elevated (range 0.0041–0.0070, mean 0.0058), consistent with organic and volcanic soil contributions to surface runoff rather than marine-origin chloride (**Figure 3**). Bees (2024) tentatively attributed elevated well chloride near the coast to saltwater intrusion, which cannot be excluded

without hydraulic head data. However, the Cl/Na ratios in high-Cl wells (mean 1.62, below the seawater value of 1.81) suggest preferential sodium release from plagioclase weathering, which is more consistent with prolonged rock-water interaction in marine-influenced basalt than with simple seawater dilution (Davis et al., 1998). Dike-impounded water, which would also show elevated ions and near-seawater ratios due to long residence times in marine basalt, cannot be excluded as a contributing source in some wells.

Two springs (Spring-3 and Spring-4) show inverted Na/Cl chemistry ($Cl/Na = 0.47 - 0.57$), where sodium substantially exceeds chloride. This is characteristic of plagioclase feldspar weathering in young basalt (Hem, 1985; Scholl et al., 1996), which releases sodium without a corresponding chloride release. This distinguishes these springs from both basal wells and streams and is consistent with a perched or intermediate groundwater source with a longer basalt contact time than surface runoff but without the marine-influenced ion load of the basal lens. The chloride distribution and major ion cross plots are shown in Figures 1 through 3.

The main statistical limitation is the small ion dataset ($n = 26$). The t-test results are statistically strong, but the sample size means the mean estimates carry substantial uncertainty, as reflected in the wide standard deviations in Table 2. A larger dataset with ion samples co-located with the isotope samples could strengthen the spatial analysis. We could also use well depth and screened interval data to inform perched versus basal assignment for the low-Cl wells on chemistry alone.

Table 4. Per-sample chloride, sodium, Cl/Na ratio, bromide, and Br/Cl ratio for all ion samples. Seawater reference values shown for comparison.

Type	Sample	Cl (mg/L)	Na (mg/L)	Cl/Na	Br (mg/L)	Br/Cl
Well	Well-1	150.5	81.7	1.84	0.54	0.0036
Well	Well-2	137.2	78.7	1.74	0.59	0.0043
Well	Well-3	8.4	6.3	1.34	0.04	0.0048
Well	Well-4	43.6	26.4	1.65	0.01	0.0002
Well	Well-5	138.5	109.7	1.26	0.63	0.0045
Well	Well-6	49.4	30.1	1.64	0.23	0.0047
Well	Well-7	201.4	118.8	1.70	0.73	0.0036
Well	Well-8	106.3	74.7	1.42	0.44	0.0041
Well	Well-9	29.8	19.9	1.50	0.13	0.0044
Well	Well-10	204.5	120.8	1.69	0.74	0.0036
Well	Well-11	269.9	149.8	1.80	0.98	0.0036
Well	Well-12	280.7	161.6	1.74	1.06	0.0038
Well	Well-13	46.6	27.9	1.67	0.18	0.0039
Stream	Stream-1	23.6	15.8	1.50	0.14	0.0059
Stream	Stream-2	15.8	12.1	1.31	0.10	0.0063
Stream	Stream-3	11.5	7.9	1.45	0.08	0.0070
Stream	Stream-4	12.5	8.5	1.46	0.07	0.0056
Stream	Stream-5	7.2	5.1	1.42	0.03	0.0041
Stream	Stream-6	13.4	9.8	1.37	0.08	0.0060
Spring	Spring-1	8.4	6.3	1.34	0.05	0.0060
Spring	Spring-2	12.9	8.1	1.59	0.10	0.0078
Spring	Spring-3	35.5	62.6	0.57	0.19	0.0054
Spring	Spring-4	30.9	65.8	0.47	0.47	0.0152
Spring	Spring-5	17.3	12.0	1.44	0.11	0.0064
Spring	Spring-6	19.1	13.2	1.44	0.10	0.0052
Spring	Spring-7	17.0	14.3	1.19	0.07	0.0041
Reference	Seawater	19000	10500	1.81	65	0.0034

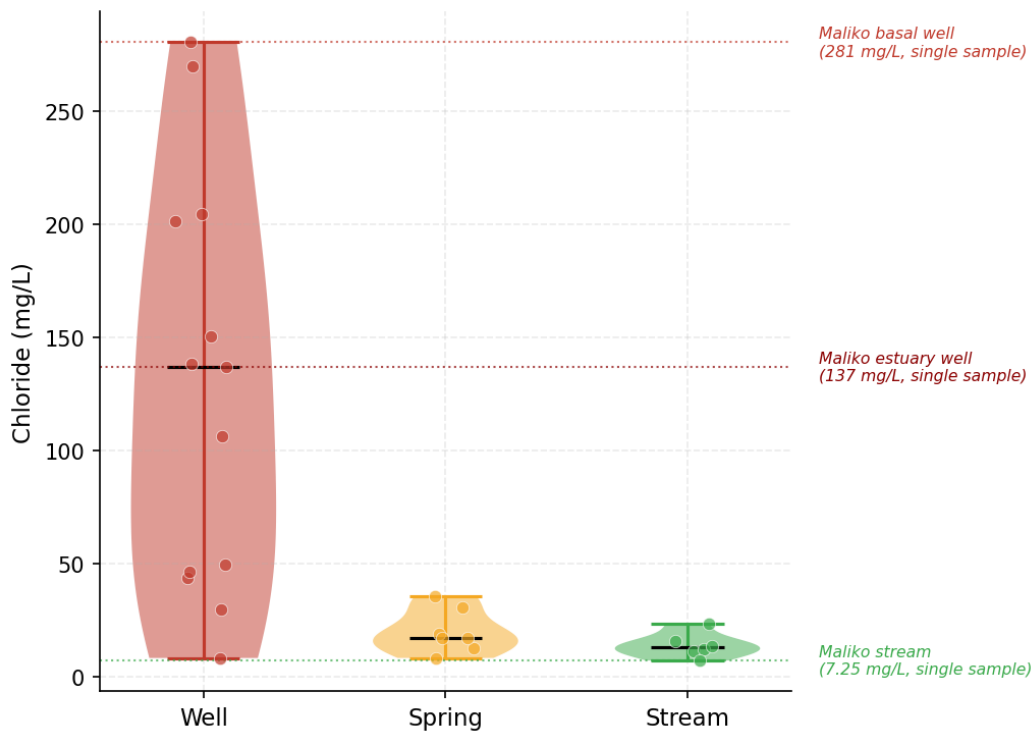


Figure 1. Chloride concentration distributions by water source type.

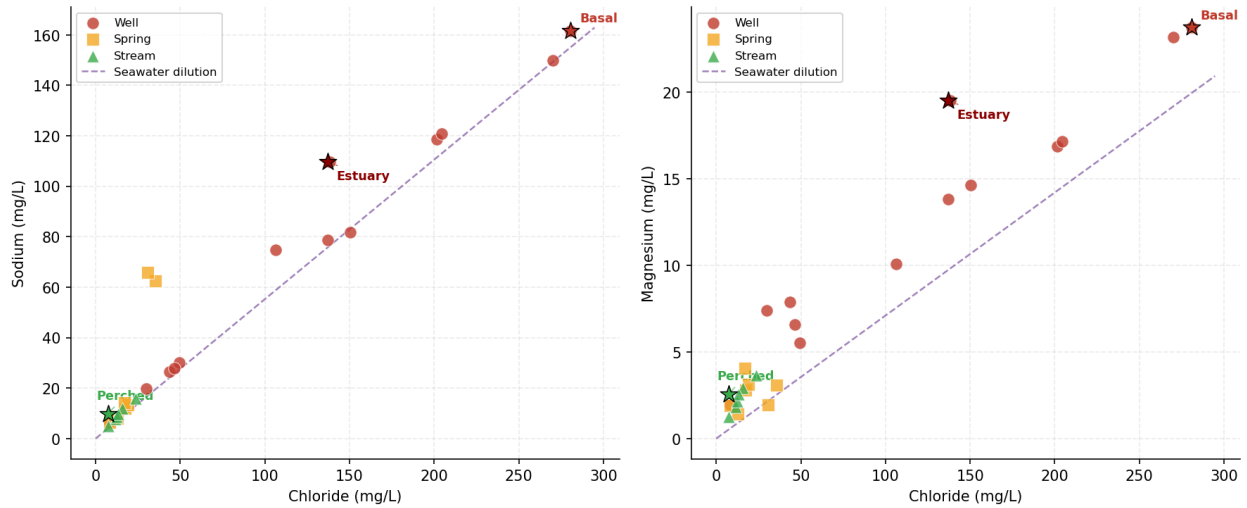


Figure 2. Major ion cross-plots (chloride vs. Sodium [left]; chloride vs. Magnesium [right]) for wells, springs, and streams. Seawater dilution line shown for reference. Maliko Gulch "end-member" samples are marked with stars.

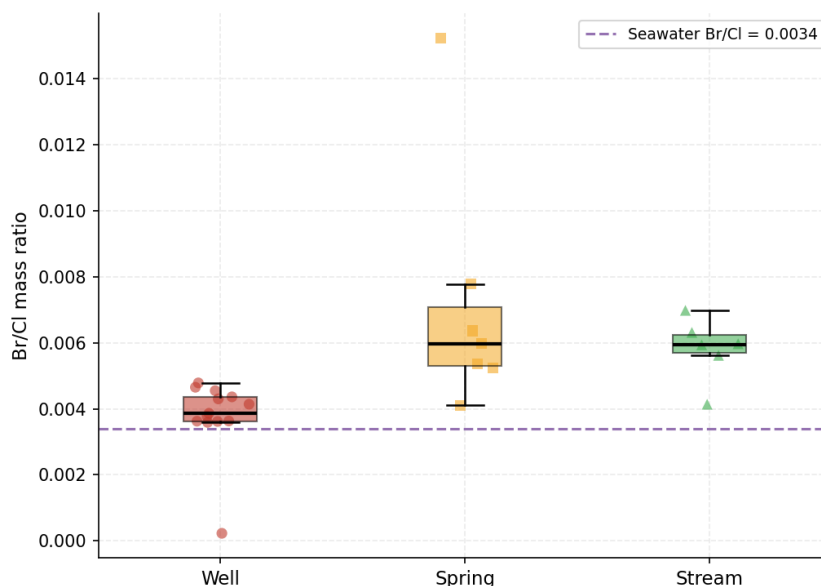


Figure 3. Br/Cl ratio by sample type. Well values (mean 0.0038) are close to the seawater reference (0.0034), consistent with marine-influenced basalt rock-water interaction. Stream values (mean 0.0058) are elevated, consistent with organic and volcanic soil contributions.

4.2 Line 2: Stable Isotopes in Ha'ikū

Isotope values from 168 samples were compared between wells and surface water (streams and springs) using unpaired t-tests applied separately to $\delta^{18}\text{O}$ and $\delta^2\text{H}$. This was done twice: once for the full dataset and once for a Ha'ikū-only spatial subset. The Ha'ikū subset is defined using the CWRM (Commission on Water Resource Management) aquifer boundary between the Ha'ikū and Honopou aquifer systems, which separates the Ha'ikū basal aquifer from the aquifer systems to the east. This boundary is consistent with the community boundary shown in Bees (2024, Fig. 6). Applying the spatial subset is important because the two communities have geochemically different aquifer behavior: pooling them in a single test masks the Ha'ikū signal, as shown by the contrasting p-values in **Table 5**.

Bees (2024) ran unpaired t-tests by region and found a statistically significant difference in Ha'ikū ($\delta^{18}\text{O}$ $p = 8.1 \times 10^{-5}$, $\delta^2\text{H}$ $p = 6.8 \times 10^{-4}$) and no significant difference in Huelo. This reanalysis replicates that finding with similar results. The full-dataset result remains non-significant ($\delta^{18}\text{O}$ $p = 0.12$), confirming that spatial subdivision is the appropriate approach.

Ha'ikū wells have mean $\delta^{18}\text{O}$ of -3.44 ‰ (range -3.80 to -2.90 ‰), while Ha'ikū surface waters have mean $\delta^{18}\text{O}$ of -2.76 ‰ (range -4.00 to -2.50 ‰). The well values are more depleted (more negative), consistent with recharge from higher elevation precipitation on Haleakalā before the water enters the basal aquifer. Elevation effects on stable isotopes in Hawaiian volcanic systems have been documented by Scholl et al. (1996, 2002) and Niu et al. (2017), who found similar altitude-related depletion gradients across northeast Maui. The magnitude of the separation (~ 0.7 ‰ in mean $\delta^{18}\text{O}$) is consistent with recharge at several hundred meters' elevation difference, broadly compatible with the Haleakalā recharge area for the basal lens.

Table 5. Stable isotope t-test results: Ha'ikū wells vs. Ha'ikū surface water (primary), and full dataset wells vs. surface water (for comparison).

Comparison	Isotope	t	p-value	Significant?
Ha'ikū: Wells vs. Surface Water	$\delta^{18}\text{O}$	-8.709	<0.000001	Yes
Ha'ikū: Wells vs. Surface Water	$\delta^2\text{H}$	-8.525	<0.000001	Yes
Full dataset: Wells vs. Surface Water	$\delta^{18}\text{O}$	-1.456	0.149	No (includes Huelo)
Full dataset: Wells vs. Surface Water	$\delta^2\text{H}$	-2.115	0.037	Marginal (includes Huelo)

Wells in Ha'ikū are more isotopically depleted than local streams, which is consistent with the basal aquifer receiving recharge from higher elevations on Haleakalā. However, isotopic depletion alone does not prove physical separation between aquifers: deeper wells could preferentially intercept higher-elevation recharge without any aquitard separating them from the perched system. This is why the ion chemistry in Line 1 is the more direct line of evidence. Elevation effects on precipitation cannot explain the 9× chloride enrichment or the near-seawater Br/Cl ratios in wells, which require a chemically distinct source with a different rock-water interaction history. The isotope data are therefore best understood as supporting the ion chemistry finding rather than standing alone as separation evidence. Isotope distributions by sample type are shown in **Figure 4**, and their spatial distribution is shown in **Figure 5**.

Values at or above 10‰ indicate that the water's isotopic composition has not been significantly modified by evaporation since it fell as rain. All sample types in this dataset (precipitation, streams, springs, and wells) have d-excess values above 10‰ (Table 1, **Figure 6**), which rules out bulk evaporation as an explanation for any isotopic differences observed between sample types, including the enriched isotopic signature in the down-gradient Maliko Gulch well relative to the mixing model prediction.

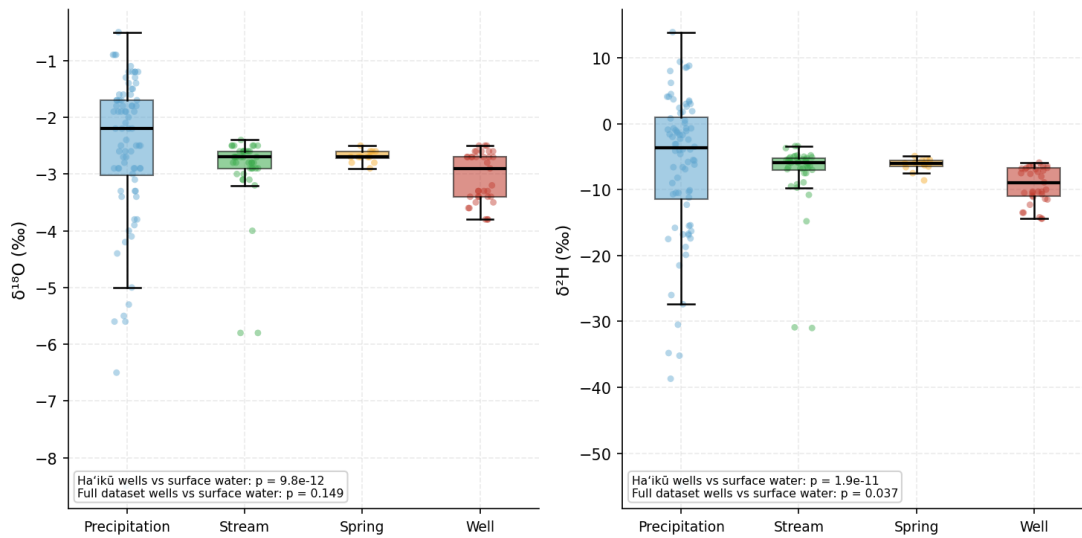


Figure 4. Stable isotope distributions ($\delta^{18}\text{O}$ [left] and $\delta^2\text{H}$ [right]) by sample type for all 168 samples. Wells are the most depleted group. The overlap between Huelo wells and surface waters is visible; the Ha'ikū subset analysis separates these populations.

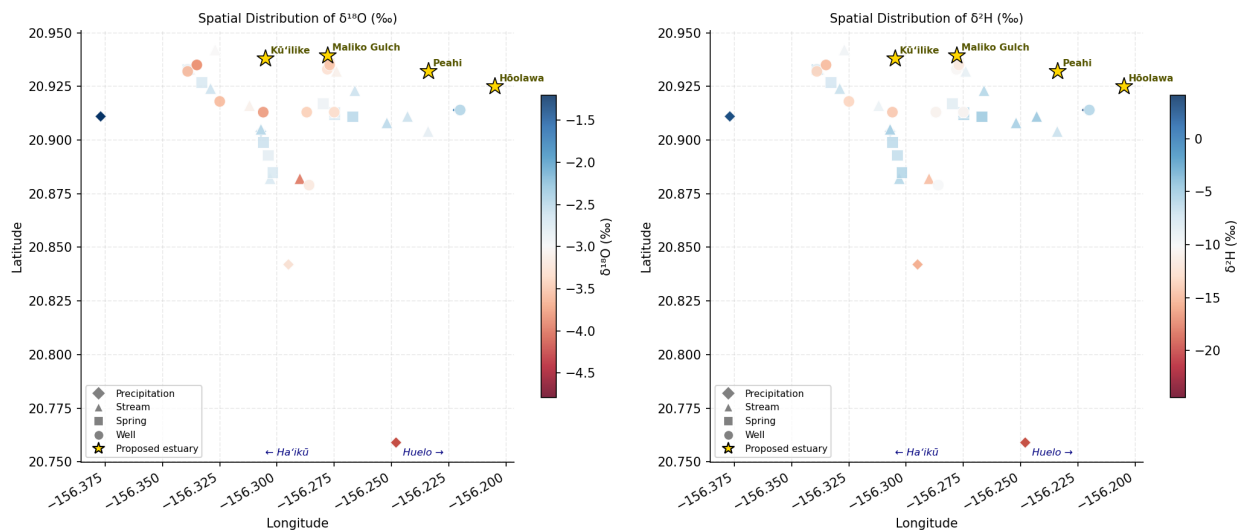


Figure 5. Spatial distribution of $\delta^{18}\text{O}$ values (left) and $\delta^2\text{H}$ values (right) across the study area. Ha'ikū wells (western cluster) are more depleted than surrounding surface waters. Gold stars indicate proposed future estuary sampling locations at Maliko Gulch, Peahi, Hōolawa, and Kū'ike.

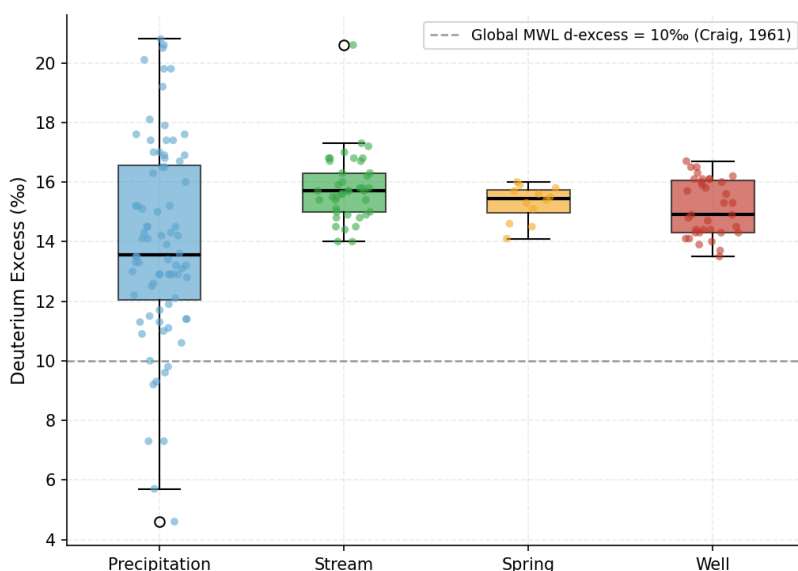


Figure 6. Deuterium excess by sample type (MWL = meteoric water line).

4.3 Line 3: Temporal Stability of Wells

If the basal aquifer is an isolated reservoir with a long groundwater residence time, then well isotope values should remain stable across seasons even while surface waters fluctuate with rainfall. A water body that cannot respond to seasonal inputs is hydraulically buffered from the surface, regardless of the specific mechanism of that buffering. Niu et al. (2020) documented the same pattern in the same study area using a longer record: basal wells showed no temporal variability in $\delta^{18}\text{O}$ or $\delta^2\text{H}$, while precipitation and springs showed clear seasonal signals. This reanalysis replicates their finding using the Bees (2024) 20-month dataset.

Standard deviation of $\delta^{18}\text{O}$ was calculated separately for wells and streams across the full record (November 2022 – July 2024). Monthly mean values were plotted over time to visualize any systematic drift or seasonal response. The analysis is descriptive: the goal is to determine whether well values respond to the seasonal precipitation signal that is visible in stream values, not to quantify the degree of isolation precisely. Well $\delta^{18}\text{O}$ standard deviation is ± 0.44 ‰ across the full record, compared to ± 0.71 ‰ for streams. Individual stream samples reach -5.8 ‰ during high-rainfall events, a shift of more than 3 ‰ from the dry-season baseline, while the most depleted well sample over the same period reaches -3.80 ‰. Well values show no systematic drift or seasonal excursions over the 20-month record. This pattern is consistent with Niu et al. (2020) and agrees with the Bees (2024) observation that wells vary less than precipitation and streams. Temporal variability is shown in **Figure 7**.

Temporal stability alone does not constrain aquitard permeability or recharge rate. A large-volume perched aquifer with a slow turnover could show similar stability. This is the gap that carbon-14 and tritium analysis could directly address: water that is centuries old by ^{14}C age cannot be perched water undergoing active modern recharge.

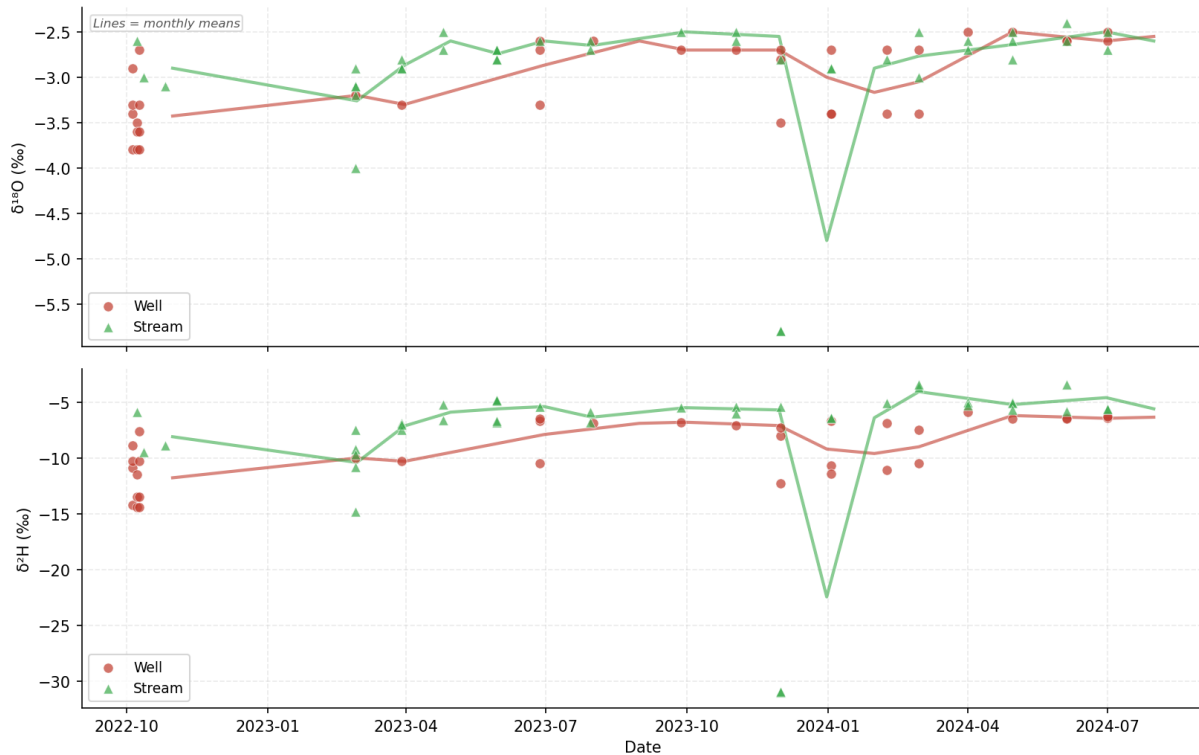


Figure 7. Temporal isotope variability in wells and streams (November 2022 – July 2024). Well $\delta^{18}\text{O}$ values remain stable throughout the record. Stream values fluctuate seasonally, with large negative excursions during high-rainfall events. Lines represent monthly means.

5.0 Comparing Ha'ikū and Huelo

The contrast between Ha'ikū (wells statistically distinct from surface water) and Huelo (wells not statistically distinct from surface water) is a useful regional observation that provides context for interpreting the separation evidence. It is not, on its own, direct proof of aquifer separation in either area. This is consistent with the Bees (2024) conclusion, which drew the same regional contrast.

Ha'ikū wells have mean $\delta^{18}\text{O}$ of -3.44 ‰ (± 0.23 ‰ SD), substantially more depleted than Ha'ikū streams at -2.79 ‰ (± 0.34 ‰ SD). Huelo wells have mean $\delta^{18}\text{O}$ of -2.64 ‰ (± 0.09 ‰ SD), which overlaps the Huelo stream range. Regional statistics are shown in **Table 6**.

Table 6. Regional isotope statistics: Ha'ikū vs. Huelo wells and streams

Region / Type	n (number of samples)	Mean $\delta^{18}\text{O}$ (‰)	Standard Deviation (SD)	Mean $\delta^2\text{H}$ (‰)	SD	Interpretation
Ha'ikū Wells	18	-3.44	±0.23	-11.59	±1.70	Basal aquifer signature
Huelo Wells	17	-2.64	±0.09	-6.82	±0.54	Perched or mixed signature
Ha'ikū Streams	24	-2.79	±0.34	-6.99	±2.45	Local precipitation
Huelo Streams	17	-3.11	±1.02	-8.45	±8.53	Local precipitation (variable)

The most informative aspect of this comparison is that streams are statistically similar across Ha'ikū and Huelo ($p = 0.16$), while wells differ substantially between the two areas. If the isotopic differences were driven by elevation or precipitation gradients, parallel trends would be expected in both surface water and groundwater. The absence of a parallel surface water trend points to a groundwater-specific control rather than a precipitation effect. This asymmetry is consistent with the paleosol aquitard being more effective in Ha'ikū than in Huelo, as proposed by Gingerich (1999b). The Ha'ikū/Huelo well contrast is shown in **Figure 8**.

Bees (2024) suggested that the Huelo result may reflect shallow wells tapping perched aquifers fed by surface water, or alternatively that the higher rainfall in Huelo fully saturates the aquifer, producing similar signatures across water types. This reanalysis agrees with that interpretation. The ambiguity in Huelo cannot be resolved from isotope data alone; tritium data could distinguish young perched water from old basal water for characterizing the Huelo system.

An alternative explanation for the Ha'ikū separation is that wells and streams simply sample precipitation from different elevations without a physical barrier, with deeper wells preferentially intercepting higher-elevation recharge. This is the main alternative hypothesis that the ion chemistry analysis addresses: elevation effects on precipitation would not produce the 9× chloride enrichment and the near-seawater Br/Cl ratios observed in Ha'ikū wells. Those features require rock-water interaction in a distinct, marine-influenced geologic unit, not just a higher recharge elevation.

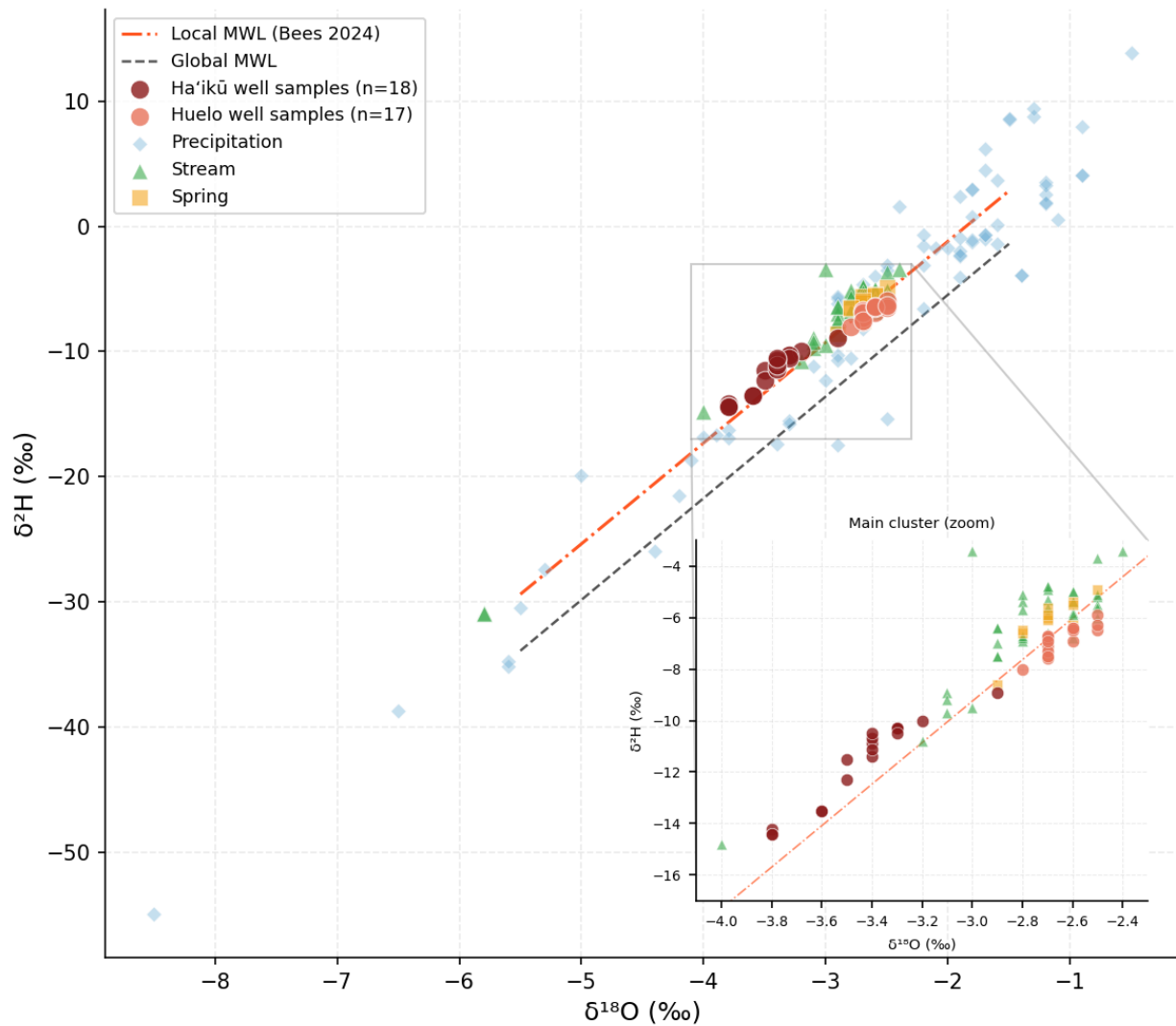


Figure 8. Dual-isotope plot distinguishing Ha'ikū and Huelo wells.

6.0 Synthesis of Evidence for Aquifer Separation

The three lines of evidence presented previously are independent in the sense that they are derived from different analytical methods applied to different physical properties of the water. Major ion chemistry reflects rock-water interaction history. Stable isotope ratios reflect condensation and precipitation altitude. Temporal variability reflects the hydrologic response time of the reservoir. Each line has limitations stated in context. The important observation is that all three are consistent with the same conclusion: Ha'ikū wells draw from a geochemically distinct water body that has a different origin, a different chemical history, and a different response to seasonal forcing than do local surface waters and springs.

The strongest individual line is the major ion chemistry: the 9× chloride enrichment and near-seawater Br/Cl ratios in wells are not readily explained by elevation effects alone and require a chemically distinct source aquifer. The stable isotope results in Ha'ikū are consistent with this, confirming that recharge histories are different, though the elevation-effects alternative cannot be fully ruled out fully from isotopes alone. The temporal stability pattern agrees with the Niu et al. (2020) finding from the same study area and adds independent support to the hypothesis that basal wells are isolated from seasonal surface inputs.

Direct sampling of estuary surface water at Maliko Gulch and other coastal GDE sites is important for answering the connectivity question; the current mixing assessment relies on a groundwater well as a proxy for estuary water, which adds an inferential step that direct sampling could eliminate. Also, carbon-14 and tritium measurements on Ha'ikū basal wells could help establish whether the water is old enough to require an isolated reservoir, which could be difficult to reconcile with the elevation-effects alternative.

One additional source of hydrogeologic complexity not addressed in the preceding statistical analyses is the potential contribution of dike-impounded water. Volcanic dikes—near-vertical, low-permeability intrusions that cut through the Honomānū Basalt and Kula Volcanics—can compartmentalize the aquifer system, impounding groundwater on their upslope side and creating discrete hydraulic units that do not communicate freely with adjacent compartments (Gingerich, 1999a; Niu et al., 2017). Water held in dike compartments can have long residence times and extended contact with marine-influenced basalt, producing elevated ion concentrations and near-seawater Br/Cl ratios similar to those observed in the high-Cl wells in this dataset. Dike compartmentalization may also explain the close-proximity well-to-well isotope variability observed at Maliko Gulch, where two adjacent wells at similar depths had $\delta^{18}\text{O}$ values of -2.6‰ and -3.5‰ , a difference more consistent with hydraulic isolation between dike compartments than with gradual mixing within a continuous aquifer. Temporal stability in well isotope values, while consistent with a large basal lens, is equally consistent with isolation within a dike compartment. The present dataset does not allow dike-impounded water to be distinguished from basal lens water on geochemical grounds alone; well construction records and hydraulic head data would be needed to assess the contribution of dike compartments to the sampled well population.

7.0 Initial Assessment of Basal Groundwater Contribution — Maliko Gulch

Maliko Gulch is the only location in the dataset where samples from three distinct hydrogeologic positions were collected in close geographic proximity: an upstream stream representing a potential perched or surface water end member, a high-chloride up-gradient well representing a potential basal end member, and a lower-chloride down-gradient well near the estuary that could represent a mixture of the two. This makes it the only feasible location in the current dataset for an initial mixing assessment. This assessment is preliminary: the down-gradient well is not a direct estuary sample, and the results should be interpreted as indicative of the direction and approximate magnitude of any basal contribution rather than as a precise estimate.

The assessment uses a two end-member linear mixing model, which assumes that the chemistry of the target sample can be expressed as a mass-balance mixture of two end members:

$C_{mix} = f \times C_{basal} + (1 - f) \times C_{perched}$, where f is the fractional contribution of basal water. This model is widely used in groundwater studies as a first-order tracer approach (Christophersen and Hooper, 1992; Sklash and Farvolden, 1979). It assumes conservative tracer behavior (no gain or loss of the tracer through rock-water reactions in the mixing zone) and only two distinct end members. Chloride is the preferred tracer because it is the most conservative major ion in groundwater and does not readily participate in mineral dissolution or precipitation reactions (Hem, 1985; Appelo and Postma, 2005). Sodium is used as a secondary check, with the understanding that sodium can be enriched by cation exchange in clay-rich sediments, making it less reliable than chloride.

The end-member concentrations are taken from individual samples, not means, because the dataset is too small to reliably estimate population means for the end-member positions. **Table 7** shows the specific samples used. The upstream stream (Stream-5; Cl = 7.25 mg/L) is the lowest-Cl stream sample and represents the low-salinity perched end member. Well-12 (Cl = 280.7 mg/L) is the highest-Cl well and represents the high-salinity basal end member. Well-2 (Cl = 137.2 mg/L), located down-gradient near the estuary, is the mixing target.

Table 7. End-member samples used in the Maliko Gulch mixing assessment.

End Member	Role	Cl (mg/L)	Na (mg/L)	Mg (mg/L)	SO ₄ (mg/L)	δ ¹⁸ O (‰)	δ ² H (‰)
Upstream stream	Perched / surface end member	7.25	9.82	2.57	4.16	-4.0	-14.8
Up-gradient well	Basal end member	281	162	23.7	43.3	-3.6	-13.5
Down-gradient well	Estuary mixing target	137	110	19.5	40.2	-2.9	-8.9

Using these specific end members, the chloride-based estimate gives a basal fraction of approximately 48–50 % for the down-gradient well. The sodium-based estimate gives approximately 45–66%, depending on the samples selected. The full range across plausible end-member combinations is shown in **Table 8**. Because the end-member concentrations are single sample values rather than means, and because the model has only two end members (real mixing in an estuary zone likely involves more than two sources), the specific percentage should not be reported as a precise estimate.

Magnesium and sulfate were also evaluated as tracers and gave higher apparent basal fractions (80–92%). These results are not used because both tracers are likely non-conservative in this setting: magnesium is enriched by water-rock interaction with basalt in the coastal zone (Appelo and Postma, 2005), and sulfate is subject to microbial sulfate reduction in the organic-rich coastal sediments, which removes sulfate from solution and inflates the apparent basal fraction. These mechanisms are well-documented in coastal groundwater mixing studies (Slomp and Van Cappellen, 2004).

Table 8. Sensitivity of the chloride-based mixing estimate to end-member selection.

Perched end-member Cl (mg/L)	Basal end-member Cl (mg/L)	Estimated Basal Fraction
7.2 (Stream-5, lowest observed)	280.7 (Well-12, highest observed)	48%
7.2 (Stream-5, lowest observed)	150.5 (Well-1, lowest high-Cl well)	91%
14.0 (stream mean)	280.7 (Well-12, highest observed)	46%
14.0 (stream mean)	150.5 (Well-1, lowest high-Cl well)	90%
23.6 (Stream-1, highest observed)	280.7 (Well-12, highest observed)	44%
23.6 (Stream-1, highest observed)	150.5 (Well-1, lowest high-Cl well)	90%

The full mixing model results, including predicted versus observed isotope values, are shown in **Figure 9**. The observed isotope values in the down-gradient well are more enriched (less negative) than predicted by the chloride-based mixing fraction ($\Delta\delta^{18}\text{O} = +0.91\text{‰}$, $\Delta\delta^2\text{H} = +5.28\text{‰}$). Seawater mixing is negligible (≤ 0.6 by chloride). Deuterium excess values above 10‰ for all sample types (Figure 6) rule out bulk evaporation as an explanation for the isotopic enrichment. The most likely explanation is that the upstream stream used as the perched end member is more isotopically depleted than the actual perched water reaching the estuary zone, which likely has a longer subsurface flow path and a slightly more enriched signature. If the true perched end member is more enriched than the stream sample, the mixing model would shift the estimated basal fraction upward, not downward.

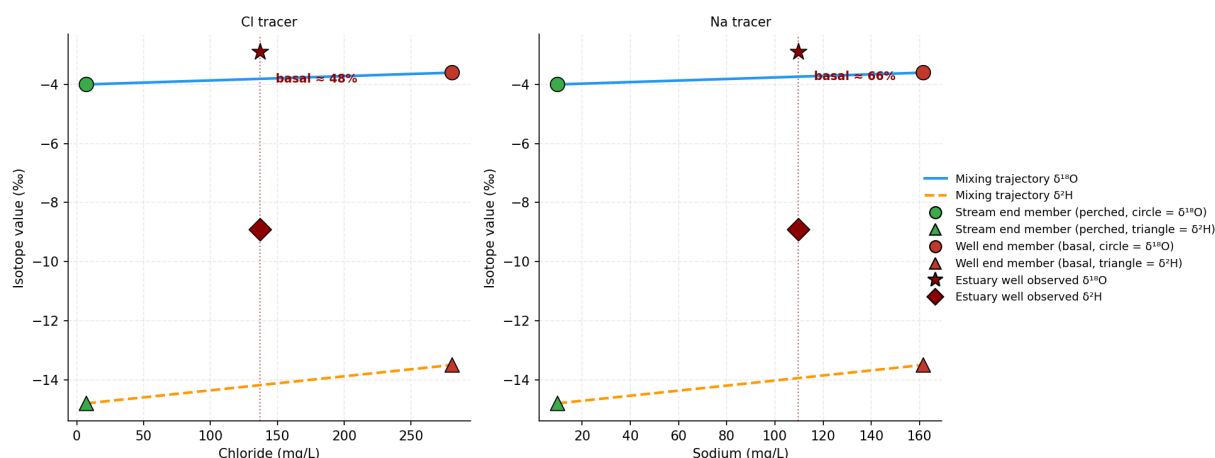


Figure 9. Maliko Gulch two end-member mixing assessment (chloride [left] and sodium [right] tracers). Mixing trajectories connect the stream (perched end member) and up-gradient well (basal end member). The down-gradient estuary well plots above the mixing trajectory, consistent with a slightly more enriched perched end-member than the upstream stream sample used here.

8.0 Conclusions

Major ion chemistry is the most direct and robust line of evidence for geochemical distinction between Ha'ikū basal wells and surface waters. All seven ions tested are significantly different between wells and surface waters ($p < 0.01$), with mean well chloride nine times higher than streams. Cl/Na ratios in high-Cl wells approach the seawater value, and Br/Cl ratios are close to the seawater reference, consistent with rock-water interaction in marine-influenced Honomānū Basalt. This result is robust across the full dataset and does not depend on spatial subdivision. It is consistent with the Bees (2024) ion chemistry finding and extends it with ratio analysis.

Stable isotopes in Ha'ikū show a statistically significant difference in recharge signatures between wells and surface waters ($p < 10^{-6}$), consistent with the ion chemistry finding. This replicates and strengthens the Bees (2024) result. The same test applied to the full dataset is not significant because Huelo wells have enriched signatures that overlap surface water; the Ha'ikū-only spatial subset is the appropriate primary comparison for this area. The elevation-effects alternative—that wells and streams simply sample precipitation from different altitudes without a physical barrier—is not ruled out by isotopes alone but is substantially weakened by the ion chemistry.

Well isotope values are stable over the 20-month record while stream values fluctuate seasonally, consistent with an isolated reservoir. This agrees with Niu et al. (2020), who documented the same pattern in the same study area using a longer record.

An initial two end-member mixing assessment at Maliko Gulch indicates that the down-gradient coastal well chemistry is broadly consistent with a substantial basal groundwater contribution, with chloride-based estimates ranging from approximately 44–91 depending on end-member selection. The wide range reflects genuine uncertainty in the choice of end-member samples; the qualitative conclusion that basal water contributes meaningfully to the coastal well zone is more defensible than any specific percentage. Direct estuary sampling at Maliko Gulch, Peahi, Hōolawa, and Kū'ike is the most important remaining data gap for the GDE connectivity question.

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