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An Investigation and Comparison of Stable Isotopes in Meteoric Waters and Groundwaters from Southern Washington

Emily E. Smoot
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An Investigation and Comparison of Stable Isotopes in Meteoric Waters and Groundwaters from Southern Washington

by

Emily E. Smoot

An undergraduate honors thesis submitted in partial fulfillment of the
requirements for the degree of Bachelor of Science

in

University Honors

and

Geology

Thesis Advisor

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Portland State University

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Abstract

A main source of freshwater in the Pacific Northwest is the Columbia River Basalt Group aquifer system. The semi-arid region of eastern Washington has undergone heavy groundwater depletion in recent decades due to increasing population and expanding agricultural use. Aggressive mining has resulted in drawdowns of up to 30 meters.

By using stable isotopes oxygen-eighteen (^{18}O) and deuterium (D), this study confines the timing of groundwater precipitation and proposes an explanation for why drawdowns are so significant. The isotopic composition of meteoric water is compared to groundwaters from southeast Washington. The two populations are statistically different ($p < 0.001$, $\alpha = 0.05$). The isotopic composition of groundwaters from the deepest wells (< -150 m msl) are isotopically lighter than meteoric waters and not achievable by recharge under the current climate. These deep groundwaters are interpreted to have precipitated during the Last Glacial Maximum in the late Pleistocene and finished precipitating roughly 5 ka. Thus, replenishment of the aquifer cannot be expected to keep pace with extraction.

Additionally, this research examines the elevation response in the stable isotope signature of meteoric water along the 47° N latitude by computing three lapse rates for ^{18}O for the windward and leeward sides of the Cascade Range. The windward lapse rates are -6.4 ‰/km ($R^2 = 0.72$) for elevations below 1300 meters (amsl), and -2.5 ‰/km ($R^2 = 0.88$) for elevations above 1300 meters (amsl). The leeward lapse rate is 12.9 ‰/km ($R^2 = 0.70$), suggesting minimal air mass mixing over the Cascade Range during transport.

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1. Introduction

1.1 Introduction

Groundwater in the Columbia River Basalt Group (CRBG) aquifers represents a substantial source of the Pacific Northwest's fresh water supply (Tolan et al., 2009; Vaccaro, 1999). Over time, growing demand and heavy pumping have resulted in significant declines in groundwater levels, particularly in the more arid regions east of the Cascade Mountains where "drawdowns" of nearly thirty meters have been reported (Papadopoulos & Associates, 2012). This amount of well drawdown is substantial, and further declines are projected as groundwater demands increase in the future. The current rate at which wells are being pumped is unsustainable, as the aquifers are not replenishing to keep up with the demand (Papadopoulos & Associates, 2012; Lum et al., 1990; Larson et al., 2000).

The issue of aquifer replenishment could be due to several factors, including excess pumping, changing climate regimes, and/or long recharge rates (Papadopoulos & Associates, 2012; Gat, 1996; Vaccaro, 1999). Determining which of these possibilities is the most impactful will influence water usage practices aimed at avoiding future supply deficiencies. Water will always be a necessity, and it is important to expand our knowledge of our natural storage systems as much as possible.

The isotopic chemistry of waters provides an important tool for understanding the complicated dynamics of source waters, aquifer recharge and flow. One important method is the determination and modeling of isotopic lapse rates, the relationship between elevation and isotopic composition of meteoric waters. Currently, there are two lapse rates presented for the state of Washington, one for the Olympic Peninsula (Sharp et al., 1960) and one that combines data along both the 48° and 45° north latitudes (Bershaw et al., 2020). This leaves a rather wide gap (3° of latitude) in the data across the state of Washington and

limits our understanding of water isotope chemistry in this dynamic region. Solidifying this relationship allows for the exploration of how precipitation is changing as vapor masses travel over our continent. These changing masses have a trickle-down effect; the changing composition of the air mass affects the isotopic composition of meteoric water bodies, and the aquifers which they replenish. Changing isotopic composition is a way one can narrow the source waters of an aquifer and determine if these waters may have been precipitated under a different climate regime. Thus, the isotopic composition becomes an intimate component of the hydrology of the area.

1.2 Purpose and Scope

The first goal of my study is to better understand the recharge dynamics of the CRBG aquifer system in southcentral Washington. Specifically, I will compare the stable isotopic signatures of CRBG groundwaters with those of modern meteoric water by examining deuterium (D) and oxygen-eighteen (^{18}O) ratios. I hypothesize that the groundwaters will have lighter isotopic signatures than the meteoric waters. The delta (δ) values for oxygen-eighteen and deuterium for groundwaters will be more negative than the corresponding values of modern meteoric waters because the fractionation of the isotopes occurred at a lower temperature, suggesting that the groundwater being withdrawn today began precipitating during a colder climate, likely more than 11.6 ka, prior to the start of the Holocene epoch (Larson, et al., 2000; Douglas et. al., 2009; Brown et al., 2011).

The implications of this study, if the primary hypothesis is supported, would be that much of the groundwater currently pumped from CRBG aquifers beneath southcentral Washington was precipitated during the Pleistocene. Because of the change in climatic conditions, (1) recharge to these aquifers cannot be modeled using modern precipitation measurements nor forecasts and (2) aquifer replenishment cannot be expected to keep pace with groundwater extraction.

The second goal of this study is to add to the existing knowledge base of the use of stable isotopes in hydrology for Washington state. The study presents six isotopic lapse rates, three for ^{18}O and three for D, which expand the current knowledge base of stable isotopes in precipitation for the region. The lapse rates are calculated for the 47° N latitude for both the windward and leeward sides of the High Cascades. This latitude was chosen both because it bisects the study area for which groundwater data was obtained (Figure 1) and helps fill in the data gap for windward lapse rates in the Pacific Northwest region calculated by Bershaw et al., (2020) for the 48° and 45° latitudes and Sharp et al., (1960) for the Olympic Peninsula.

1.3 Study Area

Figure 1. A map of Washington with a blue box highlighting the area of extent for the comparison. The black dashed lines define the study area for the lapse rate data and the 47-degree latitude is denoted by the red line.

2. Background

2.1 Geology

The Columbia River Plateau (Figure 2) is underlain by the Columbia River Basalt Group (CRBG), which covers a massive area in the Pacific Northwest, extending from Idaho to the Pacific Ocean (Reidel & Tolan, 2013). The multi-layered volcanic rocks of the CRBG grace the Pacific Northwest with many unique features, including the high walls and waterfalls of the Columbia River Gorge.

Figure 2. A map showing the extent of the Columbia River Plateau (light gray).

The CRBG represent stacks of individual lava flows that poured out of fissures in eastern Oregon, Washington, and western Idaho five to seventeen million years ago (Reidel & Tolan, 2013; Vaccaro, 1999). As flows of lava traveled along the surface, the tops began to cool and

solidify; however, this outer crust would be broken up by the continued movement of the still fluid interior, forming a broken, rubble flow top (Tolan et al., 2009; Figure 3). The porosity resulting from this process, known as brecciation, is augmented by vesicles formed by degassing of the lava (Tolan et al., 2009). The porosity in the brecciated flows allows for the storage and movement of groundwater. Because these zones occur between individual lava flows, they are known as the “interflow zones” (Tolan et al., 2009; Figure 3). These interflow zones store the majority of the groundwater for the study area and the Pacific Northwest (Vlassopoulos et al., 2009; Tolan et al., 2009; Figure 3).

Figure 3. A diagram of the intraflow structures present in the Columbia River Basalt sheet flows taken from Tolan et al., 2009.

2.2 Stable Isotope Chemistry

An important method for constraining groundwater recharge conditions is to use stable isotopes. A common method used is Carbon fourteen (C^{14}) dating. The age of groundwaters within the study area has been constrained using C^{14} age dating and deep groundwaters are thought to be on the order of thousands of years old to tens of thousands of years old (Douglas et al., 2009; Brown et al., 2011). This dating method constrains the amount of time the waters have been out of contact with the atmospheric carbon and provides one with an estimate of the date the water could have been precipitated; however, C^{14} dating can have its uncertainties. Many different types of reactions occur in groundwater that can affect the accuracy of C^{14} techniques. For example, the weathering of feldspars in the surrounding rock can cause the precipitation of calcium carbonate ($CaCO_3$). This process of precipitation involves the fractionation of carbon in the system affecting the amount of C^{14} . Prevalently used models for C^{14} dating do not often account for these types of reactions, giving any calculated result an inherent uncertainty (Pearson & Hanshaw, 1970; Plummer & Glynn, 1992). Thus, an alternative method for constraining groundwater recharge conditions is using stable isotopes, which are often unaffected by water-rock interactions.

Stable isotopes do not spontaneously decay like their radioactive counterparts. Stable isotope composition is affected by numerous factors such as evaporation, precipitation, temperature, and elevation (Clark & Fritz, 1999; Clark, 2015). The isotopes fractionate; isotope fractionation is the partitioning of heavy and light isotopes between two phases in a natural system. One example is ^{18}O and ^{16}O in the liquid and vapor phases of water (Urey, 1947; Clark & Fritz, 1999). Energy is needed to separate isotopes from their ideal interatomic distance. The heavy isotopes have a stronger bond and require a greater amount of energy to dissociate than a light isotope. Consequently, the heavy isotopic species are typically partitioned into the more

condensed phases, such as into the liquid phase in vapor-liquid reactions, because of this greater bond strength (Clark & Fritz, 1999; Clark, 2015). These fractionation events occur during evaporation and precipitation and when vapors travel inland over continents for long periods of time or experience a change in elevation when traveling over topography.

Fractionation is heavily influenced by temperature because it is a thermodynamic reaction (Clark & Fritz, 1999). At lower eustatic temperatures, the oceans tend to have heavier isotopic values while precipitation and the ice sheets experience lighter values because the heavier bonds are more difficult to break and fewer leave their initial liquid state (Clark & Fritz, 1999). Similarly, increasing elevation causes isotopic composition to become lighter or more negative due to the drop in atmospheric temperature with increased elevation.

Because of fractionation, stable isotopes make good proxies for paleoclimates and paleoelevations (Poage & Chamberlin, 2001; Garzione et al., 2000; Clark, 2015). By evaluating the isotopic composition of the groundwater for a region, one can determine if the recharge waters for a system were sourced from high or low elevations or deposited during climates differing from the present (Clark & Fritz, 1999; Poage & Chamberlin, 2001; Larson et al., 2000; Lecher et al., 2018).

Due to the fractionation processes described, ^{18}O and D in precipitation covary is a predictable manner. At the global scale, this covariance results in the Global Meteoric Water Line (GMWL) (Craig, 1961). The GMWL is described by the following equation:

$$\delta D = 8\delta^{18}\text{O} + 10 \quad (1)$$

While the GMWL describes the variation in the stable isotope signature of meteoric waters at the global scale, isotopic variation within specific regions are best described by the Local Meteoric Water Line (LMWL). This LMWL is created by plotting the measured ratios of D and ^{18}O from a specific region. Thus, providing a benchmark or normal for the isotopic composition of the

area. The LMWL of a region can then be compared to the GMWL to determine if certain processes are more prevalent than others such as evaporation and equilibrium fractionation (Clark and Fritz, 1999).

3. Methods

3.1 Data

The data used in this research was collected from three main sources. The first source is a hydrochemistry data set from Vlassopoulos et al. (2009), which includes stable isotope ratios for seventy-two groundwater samples collected from southcentral Washington state, between -120.0° and -117.5° longitude and 48.0° and 46.0° N latitude (Figure 4). Surface water data was used instead of direct precipitation for both the determination of lapse rates and the comparison with groundwater data because the surface waters effectively average precipitation values overtime. Additionally, there was a lack of direct precipitation data within the study area and very few sites were readily available for retrieval. The meteoric water data ($n = 131$) retrieved for comparison with the groundwater data came from the WaterIsotopes database and the Global Network of Isotopes in Rivers (GNIR) database (IAEA, 2020). The data sites were queried for river, stream and lake samples located between 46.0° and 48.5° N latitude and -121.0° and -117.0° longitude (Figure 4).

Figure 4. The location of groundwater samples (orange triangles) and Meteoric water samples (blue circles) used for comparison. Gold stars represent the locations of cities.

Similarly, meteoric water data for determining lapse rates ($n = 113$) was obtained from the WaterIsotope Database (WaterIsotopes, 2020) for rivers, streams and lakes located between 46.5° and 47.5° N latitude and -124.0° and -117.0° longitude (Figure 5).

A comparable query with the same coordinate boundaries was used on the data site for time series data from GNIR (IAEA, 2020). Any duplicate data from GNIR was removed before combining the two datasets. Both retrieved datasets had incomplete elevation measurements. New elevations for the sample sites were determined based on existing GPS coordinates and the corresponding surface elevations obtained from Google Earth Pro.

Figure 5. Windward low elevation samples less than 1300 m (blue), windward high elevation samples greater than 1300 m (red) and leeward samples (black). Gold stars represent the locations of cities.

All of the isotopic data used in the study are reported in delta (δ) notation with units of per mille (‰). The samples have been reported relative to the Vienna Standard Ocean Water (VSMOW) for ^{18}O and D. These sample values were calculated using the following equation or an equivalent, where ^{18}O is the heavy oxygen isotope and ^{16}O is the light oxygen isotope.

$$\delta^{18}\text{O} = \left(\frac{(^{18}\text{O}/^{16}\text{O})_{\text{sample}}}{(^{18}\text{O}/^{16}\text{O})_{\text{reference}}} - 1 \right) \cdot 1000\text{‰ VSMOW} \quad (3)$$

3.2 Isotopic Lapse Rate

The windward and leeward samples were split on the -121.0° longitude line as this corresponds with the eastern boundary of the Cascades Range and groups the high elevations together. To account for evaporation effects on the isotopic compositions of the

meteoric waters, the local meteoric water lines (LMWL, or trendline of local meteoric water data on a δD versus $\delta^{18}O$ plot) for both the windward ($n = 67$) and leeward samples ($n = 46$) were compared to the GMWL established by Craig (1961) to be,

$$\delta D = 8\delta^{18}O + 10 \quad (2)$$

The deuterium excess or d-index (d) was computed for each of the samples using following equation (Dansgaard, 1964):

$$d = \delta D - 8\delta^{18}O \quad (3)$$

Once the deuterium excess was computed for each of the samples, a mean and standard deviation were computed. Samples were excluded from the LMWL and lapse rate calculations if they were one or more standard deviations less than the mean. These points were removed from the calculations because the low or negative deuterium excess suggests evaporation. The selected samples were then graphed against their corresponding sample elevations. If samples were taken at the same location over a period of time these samples were averaged before plotting. The slope of the linear trendline then supplies the lapse rate for the samples (Poage & Chamberlin, 2001; Garizone et al., 2000).

3.3 Comparison

The analysis for the comparison was completed using R and Excel. The analytic techniques used were the Mann-Whitney-U test, box and whisker plots, and linear regressions. These tools were used to determine the statistical significance of the difference between the meteoric water and the groundwater samples. Additionally, the isotopic values of the samples from the meteoric water population were plotted against time when measurements were taken over an extended interval of time of one month or greater. These plots were then used to determine any seasonal variance of the isotope ratios within the rivers. The isotopic value ranges for winter precipitation, November to

March, were compared to the groundwaters at the shallowest depths that could potentially be influenced by seasonality. Statistical significance for the groundwater versus well bottom elevation plots was determined with linear regressions.

4. Results & Discussion

4.1 Isotopic Lapse Rates

4.1.1 Windward Lapse Rate

A majority of the data from samples collected on the windward side of the Cascade Range closely follow the GMWL; however, the LMWL has a lower y-intercept of 7.44 ‰ for δD (Figure 6). Eight samples with the lowest deuterium excess values followed a trend with a lower slope and were deemed to have been impacted by evaporation; these samples (red x's in Figure 6) were not used in calculation of the lapse rate.

The lapse rate for the windward side of the Cascade Range is showing to be roughly -6.4 ‰/km for mid and low elevations (< 1300 m), and -2.5 ‰/km for high elevation samples, greater than 1300 m (Figure 7). The R^2 value for the relationship between ^{18}O ratios and mid to low elevations is 0.72, while the R^2 equals 0.88 for high elevations (Figure 7).

There are several possibilities for why these samples do not fit a linear trend better. Of these, the dominant issues are the sampling elevation relative to the headwaters for a stream and the influence of snow sublimation on the isotopic composition of the meteoric waters. The first issue of excluding the headwaters is because many of the samples were collected from easily accessible locations. In the case of the Puyallup River, its sample elevation of seven meters is drastically lower than the majority of its path for which elevation peaks at roughly 2500 meters (Dzurisin et al., 1983). The Puyallup River plotted with its sample elevation lands almost directly on the y-axis and with a $\delta^{18}O$ of -12.5 ‰. If the sample were to be plotted with its headwater

elevation, roughly 2500 meters for the Puyallup Glacier, it would lie closely along the trendline for the high elevation samples (Dzurisin et al., 1983). Doing this with some of the other samples would produce a similar result and plot the points closer to the current trendlines, thus, raising the R^2 value in the process.

The second issue that may be affecting the fit of the data to a linear trendline is due to potential snow sublimation. The sublimation of snow is suggested to enrich the isotopic composition of the snowpack and the resulting meltwaters (Lecher & Neimi, 2012). Since the western United States is snow dominated (Barnett et al., 2005), it is reasonable to assume that changes in snowpack isotope chemistry will substantially alter the stream water isotopic compositions. This enrichment due to sublimation will result in higher $\delta^{18}\text{O}$ values than anticipated for the sample elevations.

The calculated lapse rate values compare well to the lapse rates previously reported for Washington and global mountain ranges. The mid- to low-elevation lapse rate of -6.4 ‰/km compares well to the Olympic Peninsula lapse rate of -5.1 ‰/km ($R^2 = 0.89$) (Sharp et al., 1960), and the high elevation samples compare very well to the combined lapse rate for the Coast Range and High Cascades at latitudes of 45.0° and 48.0° respectively, of -3.1 ‰/km ($R^2 = 0.70$) (Bershaw, et al., 2020). Additionally, the high elevation lapse rate of -2.5 ‰/km agrees with the global lapse rate for mountain ranges of -2.8 ‰/km (Poage & Chamberlin, 2001). Additionally, similar trends are present when δD is plotted against the sampled elevation. These trends show an inverse relationship between increasing sample elevation and decreasing δD values (Figure 8). Similar patterns for D have been reported by Smith et al., (1978) in eastern California, where δD became more depleted as precipitation was sampled at higher elevations.

Figure 6. Plot of δD vs $\delta^{18}O$ showing the Local Meteoric Water Line (LMWL; blue solid line) for the windward side of the Cascade Range at a latitude of $47 \pm 0.5^\circ$ as determined from meteoric water samples (blue dots). The red X's denote meteoric water samples that had deuterium excess values one standard deviation or more less than the average, likely reflecting evaporation. The black dashed line represents the GMWL (Craig, 1961).

Figure 7. Plot of $\delta^{18}\text{O}$ vs sample elevations for the windward side of the Cascades along $47 \pm 0.5^\circ$ latitude. Two trends are apparent; the red points and line are from samples collected at greater than 1300 meters (amsl) elevation, and blue points are from samples collected below 1300 meters elevation.

Figure 8. δD vs sample elevations for the windward side of the Cascades along $47 \pm 0.5^\circ$ latitude. Red diamonds are from samples collected at elevations greater than 1300 meters (amsl), and blue diamonds are from samples collected below 1300 meters.

4.1.2 Leeward Lapse Rate

The LMWL for the leeward side of the High Cascades has a slope of 8.4 and a y-intercept of +14.2 ‰. Both of these values are higher than the GMWL slope and y-intercept, 8 and +10 ‰ respectively (Figure 9). The relatively high deuterium excess (y-intercept) suggests isotopic enrichment consistent with more arid regions (Gat & Bowser, 1991) and, thus with the modern climate of the region, arid with little precipitation outside of winter

The leeward lapse rate is 12.9 ‰/km and shows a positive relationship between $\delta^{18}O$ ratios and elevation (Figure 10). The R^2 -value for the linear relationship is 0.70. Similarly, the plot of δD versus elevation presents a direct relationship between δD ratios in per mille and sample elevation with an R^2 of 0.68 (Figure 11). The direct relationship that is present in these graphs is interpreted as ongoing Rayleigh Distillation but in a reverse manner than what is

expected on the windward side of mountains and suggests the vapor mass is adiabatically heated as it travels to lower elevations (Rowley & Garizone, 2007; Moran et al., 2007).

This type of relationship is rarely reported for the leeward side of mountain ranges. Often this relationship is not observed because of the turbulent mixing which occurs when an air mass moves over topographic barriers or due to the mixing of multiple air masses which can occur at convergent zones (Lapp et al., 2001; Moran et al., 2007; Smith, 1989). The dominant air masses for Washington state and the Pacific Northwest are maritime polar (mP) and continental polar (cP). These two air masses are expected to converge inland near the eastern boundary of western North America (Lapp et al., 2001; Moran et al., 2007). A convergence like this makes it unlikely to see the trend presented in Figures 10 and 11. Because it is present, it is expected that the dominate air mass is the mP because of the consistent trends for both the windward and leeward sides of the cascades. A cP air mass would be expected to be more negative in its isotopic composition than the values observed due to both colder temperatures and prolonged transport over the continent (Clark & Fritz, 1999).

Five similar trends were reported in the Canadian Rocky Mountains for fresh snow fall. These lapse rates for $\delta^{18}\text{O}$ range from 18 ‰/km (adjusted $R^2 = 0.18$) to 3 ‰/km (adjusted $R^2 = 0.08$) (Moran et al., 2007). It is expected that fit to a linear model is less ideal for these rates due to the varied direction of storm fronts which were both westerly and easterly (Moran et al., 2007). The trends observed over the Cascade Range also suggest that the mP air mass that travels over the High Cascades does not undergo turbulent mixing (Smith et al., 1989); turbulent mixing during transport would be an alternative reason as to why this type of relationship is not observed or poorly fits a linear trend (Moran et al., 2007). Additionally, the leeward lapse rates for both $\delta^{18}\text{O}$ and δD support an unsplit path of transport for the air mass, as splitting of the air mass would promote mixing (Smith, 1989; Figure 10 & Figure 11).

Figure 9. Graph of the leeward LMWL (black), with heavily evaporated samples (red) and the GMWL for reference as a gray dashed line.

Figure 10. Graph of the leeward lapse rate for the Cascade Range along $47 \pm 0.5^\circ$ latitude.

Figure 11. Plot of δD vs sample elevations for the leeward side the High Cascades along $47 \pm 0.5^\circ$ latitude.

4.2 Isotopic Composition Comparison Between Meteoric Waters and Groundwaters in Southeastern Washington

The LMWL for the meteoric samples in the 46.0° to 48.5° latitude, and -121.0° to -117.0° bounding box is compared to the GMWL (Craig, 1961) along with the groundwater samples in Figure 12. The meteoric water samples show minimal evaporation when heavily evaporated points are removed with a slope of 8.1 with a y-intercept of $+9.4$ ‰. Heavily evaporated meteoric water samples lie nicely along the groundwater trendline (Figure 12). The groundwater follows a linear trend well with an R^2 of 0.92. Groundwater samples appear to clump near the -150 ‰ value (Figure 12).

Figure 12. Graph of δD vs $\delta^{18}O$ for the meteoric water (blue) and groundwater samples (orange). The meteoric water samples provide the LMWL for the region which is compared to the GMWL (gray dashed line) (Craig, 1960). Red Xs denote meteoric water samples that had d-indexes one standard deviation or more less than the average and were not included in the LMWL.

The following box and whisker plots (Figure 13a & Figure 13b) provide a visual representation of the differences between the meteoric waters and groundwaters. The meteoric water samples show more variability in both the deuterium and oxygen-eighteen ratios than is seen in the groundwater population. The Mann-Whitney U tests indicate a significant difference between the two populations ($p < 0.0001$; $\alpha = 0.05$) for both D and ^{18}O . As expected, the groundwater samples are isotopically lighter than the meteoric water samples (Figures 13a & 13b).

Figure 13a. Box and whisker plots comparing meteoric water and groundwater δD samples. The light blue box is meteoric water ($n = 130$), and the orange box is groundwater ($n = 55$).

Figure 13b. Box and whisker plots comparing meteoric water and ground water $\delta^{18}\text{O}$ samples. The light blue box is meteoric water ($n = 131$) and the orange box is groundwater ($n = 72$).

Figures 14a and 14b plot isotopic ratios against time to determine any change seasonally in the isotopic composition. The meteoric water samples show seasonal variation in each of the five rivers plotted using their $\delta^{18}\text{O}$ and δD values. The most predominant seasonal variations are in the Columbia River and the Yakima River (Figure 14a & Figure 14b). These variation range in differences of isotopic values with season range from 10.2 ‰ – 1.9 ‰ for deuterium and 2.5 ‰ – 0.19‰ for oxygen-eighteen. The change in ^{18}O values is very limited and may simply be due to laboratory error as the range does not exceed 2.5 ‰. However, in Cle Elum, WA seasonal variation of oxygen-eighteen was reported to be -17 ‰ in the winter and -8 ‰ in the summer, a

difference of 9‰, for precipitation and soil waters (Robertson & Gazis, 2006). The continuous mixing of the rivers sampled are potentially dampening the signal of seasonal variation making this difference hard to distinguish without more consistent sampling over time. It has been suggested that the seasonality of precipitation is not recorded in shallow groundwaters, and this is expected with the samples evaluated for this study (Takeuchi et al., 2009), but because, the groundwater samples used in this study were not taken over a synchronous period of time, it may still be investigated.

Figure 14a. A graph showing the δD ratio against time for five rivers in SE WA. The blue diamonds represent the Columbia River, yellow Xs are the Snake River, green triangles are the Okanogan River,

black circles are the Spokane River, and finally, orange squares show the Yakima River. The Columbia, Yakima, and Okanago Rivers show a fairly consistent seasonal transition of decreasing isotopic composition through the fall and end of winter and then an increasing isotopic composition in late spring and summer.

Figure 14b. Graph displaying the $\delta^{18}\text{O}$ ratio against time for five rivers in SE WA in Figure 14a. A similar seasonal trend is present distinctly in two of the five rivers.

Figures 15a and 15b plot the δD and $\delta^{18}\text{O}$ of the groundwater samples against well bottom elevation. The completed linear regressions provided p-values of 0.0001 and < 0.0001 ($\alpha = 0.05$) for the plots of $\delta^{18}\text{O}$ and δD respectively. There are two cutoffs in both graphs, showing the shallowest wells have the heaviest isotopic values with a cutoff at 500 m mean sea

level (msl), and the deepest wells have the lightest isotopic values with a cutoff of -150 m msl. For the values in-between these cutoffs, it is highly likely that groundwater mixing is occurring between aquifers at this range of well bottom elevations, thus, obscuring any clear trend between the two extremities. The shallow wells (>500 m msl) are most likely influenced by modern precipitation as their values range from -130.0 ‰ to -121.0 ‰ for deuterium and -16.8 ‰ to 15.4 ‰ for oxygen-eighteen. These values fall within the range for several of the streams and rivers examined in this study (Figure 14a & 14b). In contrast, the deeper wells (< -150 m msl) have values of -141.0 ‰ to -145.4 ‰ and -17.6 ‰ to -18.5 ‰ (Figure 15a & 15b) that are only achievable for $\delta^{18}\text{O}$ from the Columbia River during the influx of winter precipitation (December to March) which has values of -129.8 ‰ to -137.5 ‰ for δD and -17.17 ‰ to 18.05 ‰ for $\delta^{18}\text{O}$ (Figure 14a & 14b). The isotopic depletion seen in the deeper wells suggests that a colder climate was needed to achieve these values as current climate conditions do not.

Groundwaters from different wells have been age dated using C^{14} dating techniques and have a possible age range of thousands to tens of thousands of years (Douglas et al., 2009; Brown et al., 2011). Some of the deepest wells have been dated to a range of 15-33 ka using ^{14}C (Brown et al., 2011); however, ^{14}C dating of groundwaters are insufficient for a final determination due to the possibility of rock water interactions of carbonates (Pearson & Hanshaw, 1970; Plummer & Glynn, 1992). The deeper groundwaters are consistent with Larson et al., 2000, and the most depleted in oxygen-eighteen further supporting that these waters were precipitated under a different climate regime and relatively old. The majority of these waters were mostly likely precipitated during the Last Glacial Maximum, during the late Pleistocene (Lecher et al., 2018; Takeuchi et al., 2009). It is suggested that there was a shift of source air mass roughly 5 ka based on spring waters in the Olympic Peninsula. This shift is considered to be due to an increased ocean surface temperature and is closely related to the groundwater ages

estimated (Slide & Cvetic, 2011; Brown et al., 2011; Douglas et al., 2009). The proposed air mass shift is not a geographically unique climatic event as it can be correlated with other records and climate proxies that show a global warming pattern at similar time periods (Slide & Cvetic, 2011; Huntley et al. 2002). As Slide and Cvetic (2011, p. 579) note, “A review of mid-Holocene warm periods from Greenland ice cores (e.g., Huntley et al. 2002), vegetation proxies in the Americas (e.g., Grimm et al. 2001), and limnology proxies in the Americas (e.g., Fritz et al. 2001) suggest one or two warming periods between 6,500- and 4,500-years BP. These temperature optima are observed more prominently in various climate proxies in Europe (e.g., Negendank, 2004).”

Figure 15a. Plot of δD against well bottom elevation in meters to mean sea level. Black dashed lines represent proposed cutoffs at -150 m and 500 m.

Figure 15b. Graph of $\delta^{18}\text{O}$ against well bottom elevation in meters to mean sea level (msl). A slight increasing trend can be inferred. Black dashed lines represent proposed cutoffs at -150 m and 500 m.

5. Conclusions

The three isotopic lapse rates computed for this study help broaden our understanding of stable isotopes in the Pacific Northwest. The windward lapse rate for $\delta^{18}\text{O}$ at low to mid elevations is -6.4 ‰/km ($R^2 = 0.72$) and is comparable to previously reported lapse rate of -5.1 ‰/km ($R^2 = 0.89$) for the Olympic Peninsula (Sharp et al., 1960). The high-elevation windward lapse rate for $\delta^{18}\text{O}$ of -2.5 ‰/km ($R^2 = 0.88$) compares very well with the combined Coast Range and High Cascades lapse rate of -3.1 ‰/km ($R^2 = 0.70$) (Bershaw et al., 2020) and the global average for mountain ranges, which is -2.8 ‰/km (Poage & Chamberlin, 2001). The leeward lapse rate, 12.9 ‰/km ($R^2 = 0.72$), provides new insight on the possibility that minimal atmospheric mixing occurs over the High Cascades and that the vapor cloud travels as an unsplit mass over the topography (Moran et al., 2007; Smith, 1989).

The meteoric water and groundwater isotopic compositions are statistically significant in their differences to one another and the groundwater samples are isotopically lighter overall. Seasonal variation was seen in five of the rivers and winter precipitation values of these isotopes are closest in comparison to the shallowest wells (>500 m). Isotopic values from the deepest wells (< -150 m) are unique to themselves and not achievable with the current climatic conditions. The results of the study suggest that the groundwaters were precipitated during the Last Glacial Maximum and is supported by prior ^{14}C ages of 15-33 ka for the oldest wells and on the scale of thousands of years for the youngest wells (Douglas et al., 2009; Brown et al., 2011). It is a possibility that the precipitation for the deepest wells concluded roughly 5 ka when there was a proposed shift in the source air mass for the Olympic Peninsula from warming ocean surface temperature due to a global warming trend (Slide & Cvetic, 2011; Huntley et al. 2002). This supports that the drawdowns currently being reported in eastern Washington are substantial because aquifer replenishment cannot keep pace with current pumping practices due to a change in climatic conditions.

Future research on this topic should investigate the possible seasonality of shallow groundwaters and further inquire about the potential of air mass confluence altering the isotopic compositions. Additionally, the potential of a wetter climate during the Last Glacial Maximum affecting recharge rates of aquifers should be examined.

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Appendix A. Groundwater data used for isotopic comparison (Vlassopoulos et al., 2009).

Site Number	Sample	Collection Date	Longitude	Latitude	Ground surface elevation (m msl)	Well bottom depth (m msl)	Well bottom elevation (m msl)	δD (per mille)	$\delta^{18}O$ (per mille)
464928119103201	BA050	3/15/83	-119.1761246	46.82430750	320	369	-49	-147.0	-18.0
465206118524401	BA073	5/24/83	-118.8880572	46.87347516	434	409	25	-142.0	-18.0
465206118524401	BA074	9/9/82	-118.8880572	46.87347516	434	409	25		-17.9
465253118420202	BA081	3/17/83	-118.7030488	46.88069820	504	183	321	-137.0	-18.0
465342118145402	BA090	5/25/83	-118.2471884	46.89348360	475	61	414	-126.0	-15.9
465342118145402	BA092	8/5/82	-118.2471884	46.89348360	475	61	414		-15.8
465347118531301	BA093	3/15/83	-118.9344480	46.82347460	396	165	232	-148.0	-19.0
465347118531301	BA095	9/8/82	-118.9344480	46.82347460	396	165	232		-18.4
465840118584601	BA115	3/17/83	-118.9811167	46.97764280	385	38	346	-132.0	-17.0
465840118584601	BA117	8/11/82	-118.9811167	46.97764280	385	38	346		-16.5
465853118365101	BA123	3/17/83	-118.6152652	46.98125599	470	311	159	-142.0	-18.0
465900118522701	BA128	8/10/82	-118.8750010	46.98319838	384	595	-210		-18.0
470048118561701	BA137	5/19/83	-118.9388927	47.01264310	433	732	-298	-144.0	-18.5
471315118282201	BA231	5/24/83	-118.4727600	47.22042619	588	104	485	-141.0	-18.2
471347118471701	BA239	3/18/83	-118.7894426	47.22986750	487	67	420	-133.0	-17.0
GB06180802	BA252	6/18/08	-118.7379000	46.76611700	405	669	-264	-145.4	-18.4
GB06190801	BA253	6/19/08	-118.7786670	47.13050000	506	313	194	-145.2	-18.4
GB06190804	BA254	6/19/08	-118.9537330	47.26083300	502	185	317	-146.1	-18.4
GB06250801	BA255	6/25/08	-118.7506500	47.10103300	501	670	-169	-144.4	-18.3
GB07080805	BA256	7/8/08	-118.264767	47.25665	545	40	504	-120.1	-14.9
463340119043901	BF034	3/10/83	-119.0755648	46.5612494	279	139	139	-135.0	-17.0
463340119043901	BF037	9/1/82	-119.0755648	46.56124940	279	139	139		-16.6

463857118474101	BF053	5/18/83	-118.7849974	46.64597330	240	91	148	-137.0	-18.0
463857118474101	BF055	8/31/82	-118.7849974	46.64597330	240	91	148		-17.6
465152118383801	BF108	3/10/83	-118.8744456	46.64291748	262	402	-140	-134.0	-17.0
465152118383801	BF110	8/31/82	-118.8744456	46.64291748	262	402	-140		-16.8
GB06180801	BF111	6/18/08	-118.8467500	46.71386700	336	250	86	-140.5	-17.9
GB06230803	BF113	6/23/08	-118.856817	46.706833	339	245	94	-140.8	-17.7
GB07080801	BF114	7/8/08	-118.8529500	46.66303300	270	305	-35	-131.2	-16.4
GB07080803	BF115	7/8/08	-118.8747830	46.64348300	267	404	-137	-134.5	-17.0
GB06230803	BF116	6/23/08	-118.856817	46.706833	339	245	94	-140.4	-17.7
GB07080802	BF117	7/8/08	-118.8529500	46.66303300	270	305	-35	-131.6	-16.4
465717119535802	BG119	8/19/82	-119.9000491	46.95679958	382	276	106		-18.7
465948119542001	BG134	8/19/82	-119.9047722	46.99902187	456	111	345		-17.2
470140119161901	BG157	5/17/83	-119.2730756	47.02208626	338	244	94	-145.0	-18.0
470236119024101	BG163	3/18/83	-119.0461202	47.04264310	367	56	310	-133.0	-17.0
471725119214501	BG352	7/26/82	-119.3525275	47.30458568	354	35	319		-15.6
471812119000002	BG354	5/18/83	-119.0008424	47.29570060	513	405	107	-147.0	-19.0
471920119320501	BG363	7/27/82	-119.5369817	47.31847210	403	564	-161		-17.2
GB06190803	BG498	6/19/08	-119.0011670	47.30481700	484	633	-149	-145.8	-18.1
GB06240805	BG499	6/24/08	-119.1932000	47.13070000	374	178	195	-128.8	-16.3
GB06240806	BG500	6/24/08	-119.1930830	47.12415000	367	381	-14	-143.8	-18.0
GB07070803	BG502	7/7/08	-119.6287000	46.89958300	315	277	38	-144.9	-18.2
GB07070804	BG503	7/7/08	-119.6296500	46.91035000	345	311	34	-138.3	-17.4
GB07150801	BG504	7/15/08	-119.0368500	46.96990000	390	253	137	-133.0	-16.9
GB07150803	BG505	7/15/08	-119.0269170	46.96576700	391	261	130	-131.3	-16.9
GB07150802	BG507	7/15/08	-119.0368500	46.96990000	390	253	137	-132.6	-16.9
471741117590201	BL025	6/20/83	-117.9821736	47.29682490	583	153	430	-136.0	-17.0
471741117590201	BL026	7/21/82	-117.9821736	47.29682490	583	153	430		-17.0
471835117583101	BL032	6/2/83	-117.9755068	47.30960278	616	54	562	-128.0	-16.0
471835117583101	BL033	7/21/82	-117.9755068	47.30960278	616	54	562		-16.0
472307118224002	BL073	6/1/83	-118.3785902	47.38542915	585	105	479	-131.0	-16.9

472638118560101	BL095	6/2/83	-118.9347295	47.44375750	522	209	313	-139.0	-17.5
473443118531501	BL144	6/3/83	-118.8897294	47.57514777	577	76	501	-135.0	-17.6
473443118531501	BL145	7/23/82	-118.8897294	47.57514777	577	76	501		-17.5
473648118452301	BL153	6/4/83	-118.7563904	47.61320437	650	348	303	-144.0	-17.9
473648118452301	BL155	9/9/82	-118.7563904	47.61320437	650	348	303		-17.8
473829118381901	BL158	6/3/83	-118.6397194	47.64126187	706	259	447	-134.0	-17.0
473832118081801	BL159	5/31/83	-118.1394164	47.63848995	737	30	707	-127.0	-16.3
473848118091901	BL162	6/1/83	-118.156362	47.64654545	735	297	437	-144.0	-18.6
474142118235502	BL172	6/2/83	-118.3997097	47.69487690	710	61	649	-121.0	-15.4
474337118454201	BL179	6/4/83	-118.7627826	47.72653927	630	51	580	-130.0	-16.8
474337118454201	BL180	7/23/82	-118.7627826	47.72653927	630	51	580		-16.6
GB06230802	BL223	6/23/08	-118.7769000	47.29191700	559	684	-126	-143.1	-17.9
GB06240802	BL224	6/24/08	-118.8624000	47.26853300	539	258	281	-145.6	-18.3
GB06240803	BL225	6/24/08	-118.899233	47.275483	543	91	452	-134.9	-17.0
GB06240810	BL226	6/24/08	-118.6247500	47.55171700	635	504	131	-143.2	-18.3
GB06240811	BL227	6/24/08	-118.6574	47.51635	627	137	490	-130.1	-16.5
GB06250802	BL228	6/25/08	-118.8467170	47.30173300	521	741	-220	-141.0	-17.6
GB06250803	BL229	6/25/08	-118.8523500	47.28251700	543	61	482	-124.7	-15.2
GB07080804	BL230	7/8/08	-118.2676330	47.27580000	582	184	397	-140.0	-17.8
GB07140801	BL231	7/14/08	-118.1562170	47.64786700	740	297	443	-143.3	-18.4

Appendix B. Meteoric water used for comparison (WaterIsotopes, 2020; IAEA, 2020).

Sample ID	Site Name	Collection Date	Latitude	Longitude	Collection Elevation (mabsl)	Type	δD (per mille)	$\delta^{18}O$ (per mille)	d	WI Analysis Source	Project ID
NRSA0809-1894	Ahtanum Creek	7/27/09 0:00	46.5270582	-120.78425		River_or_stream	-114.26	-15.51	9.80	EPA	165
CK_4224	Columbia R At Vernita Br Nr Priest Rpds Dm	9/30/85 0:00	46.63999	-119.7317		River_or_stream	-132.60	-16.74	1.32	USGS	48

CK_4225	Columbia R At Vernita Br Nr Priest Rpds Dm	12/17/85 0:00	46.63999	-119.7317		River_or_stream	-132.30	-17.17	5.06	USGS	48
CK_4234	Columbia R At Vernita Br Nr Priest Rpds Dm	5/19/87 0:00	46.63999	-119.7317		River_or_stream	-126.00	-16.54	6.32	USGS	48
CK_4220	Columbia R At Vernita Br Nr Priest Rpds Dm	1/22/85 0:00	46.63999	-119.7317		River_or_stream	-134.00	-17.55	6.40	USGS	48
CK_4231	Columbia R At Vernita Br Nr Priest Rpds Dm	11/12/86 0:00	46.63999	-119.7317		River_or_stream	-131.50	-17.26	6.58	USGS	48
CK_4218	Columbia R At Vernita Br Nr Priest Rpds Dm	9/11/84 0:00	46.63999	-119.7317		River_or_stream	-129.50	-17.05	6.90	USGS	48
CK_4221	Columbia R At Vernita Br Nr Priest Rpds Dm	3/26/85 0:00	46.63999	-119.7317		River_or_stream	-137.50	-18.05	6.90	USGS	48
CK_4226	Columbia R At Vernita Br Nr Priest Rpds Dm	1/21/86 0:00	46.63999	-119.7317		River_or_stream	-133.30	-17.56	7.18	USGS	48
CK_4219	Columbia R At Vernita Br Nr Priest Rpds Dm	11/14/84 0:00	46.63999	-119.7317		River_or_stream	-131.00	-17.30	7.40	USGS	48
CK_4229	Columbia R At Vernita Br Nr Priest Rpds Dm	7/21/86 0:00	46.63999	-119.7317		River_or_stream	-127.50	-16.88	7.54	USGS	48
CK_4233	Columbia R At Vernita Br Nr Priest Rpds Dm	3/10/87 0:00	46.63999	-119.7317		River_or_stream	-133.80	-17.67	7.56	USGS	48
CK_4227	Columbia R At Vernita Br Nr Priest Rpds Dm	3/12/86 0:00	46.63999	-119.7317		River_or_stream	-133.70	-17.66	7.58	USGS	48
CK_4230	Columbia R At Vernita Br Nr Priest Rpds Dm	9/25/86 0:00	46.63999	-119.7317		River_or_stream	-132.40	-17.50	7.60	USGS	48
CK_4236	Columbia R At Vernita Br	9/2/87 0:00	46.63999	-119.7317		River_or_stream	-130.30	-17.25	7.70	USGS	48

	Nr Priest Rpds Dm										
CK_4232	Columbia R At Vernita Br Nr Priest Rpds Dm	1/21/87 0:00	46.63999	-119.7317		River_or_stream	-130.80	-17.35	8.00	USGS	48
CK_4235	Columbia R At Vernita Br Nr Priest Rpds Dm	7/7/87 0:00	46.63999	-119.7317		River_or_stream	-125.80	-16.73	8.04	USGS	48
CK_4222	Columbia R At Vernita Br Nr Priest Rpds Dm	5/28/85 0:00	46.63999	-119.7317		River_or_stream	-126.00	-16.76	8.08	USGS	48
CK_4223	Columbia R At Vernita Br Nr Priest Rpds Dm	7/29/85 0:00	46.63999	-119.7317		River_or_stream	-126.90	-16.88	8.14	USGS	48
CK_4228	Columbia R At Vernita Br Nr Priest Rpds Dm	5/27/86 0:00	46.63999	-119.7317		River_or_stream	-125.30	-16.76	8.78	USGS	48
CK_4240	Columbia River At Richland	7/30/85 0:00	46.31278	-119.2578		River_or_stream	-128.00	-16.74	5.92	USGS	48
CK_4242	Columbia River At Richland	3/12/86 0:00	46.31278	-119.2578		River_or_stream	-134.10	-17.63	6.94	USGS	48
CK_4244	Columbia River At Richland	3/9/87 0:00	46.31278	-119.2578		River_or_stream	-134.80	-17.74	7.12	USGS	48
CK_4245	Columbia River At Richland	5/20/87 0:00	46.31278	-119.2578		River_or_stream	-125.90	-16.64	7.22	USGS	48
CK_4237	Columbia River At Richland	11/15/84 0:00	46.31278	-119.2578		River_or_stream	-130.70	-17.25	7.30	USGS	48
CK_4241	Columbia River At Richland	12/18/85 0:00	46.31278	-119.2578		River_or_stream	-129.80	-17.14	7.32	USGS	48
CK_4246	Columbia River At Richland	7/8/87 0:00	46.31278	-119.2578		River_or_stream	-125.80	-16.64	7.32	USGS	48
CK_4243	Columbia River At Richland	5/28/86 0:00	46.31278	-119.2578		River_or_stream	-126.50	-16.77	7.66	USGS	48
CK_4239	Columbia River At Richland	5/29/85 0:00	46.31278	-119.2578		River_or_stream	-125.00	-16.61	7.88	USGS	48

CK 4238	Columbia River At Richland	3/27/85 0:00	46.31278	-119.2578		River_or_stream	-136.00	-18.06	8.48	USGS	48
710866	Grimes	8/16/07 0:00	47.7286971	-119.5926	559.27	Lake	-73.58	-5.10	32.78	EPA_Corvallis	10
NRSA0809-1912	Little Bridge Creek	7/16/09 0:00	48.3849995	-120.29642		River_or_stream	-134.00	-17.44	5.49	EPA	165
711100	Medical Lake	8/30/07 0:00	47.5706872	-117.68899	731.19	Lake	-61.57	-4.19	28.05	EPA_Corvallis	10
NRSA0809-1905	Methow River	7/15/08 0:00	48.2525067	-120.11672		River_or_stream	-132.36	-17.54	7.94	EPA	165
NRSA0809-1916	Mill Creek	8/19/09 0:00	46.0652538	-118.38026		River_or_stream	-102.48	-13.34	4.28	EPA	165
17-040_7322	MMB138	8/12/16 0:00	47.66228	-117.41089	571.5	River_or_stream	-109.76	-14.54	6.55	SPATIAL	98
17-040_7327	MMB143	8/12/16 0:00	46.978086	-120.56742	458.2	River_or_stream	-94.91	-12.96	8.73	SPATIAL	98
17-040_7376	MMB192	8/21/16 0:00	48.360019	-119.58147	248.5	River_or_stream	-113.17	-13.90	-1.97	SPATIAL	98
17-040_7378	MMB194	8/21/16 0:00	47.947803	-118.98649	391.2	River_or_stream	-127.70	-16.67	5.69	SPATIAL	98
17-040_7383	MMB199	8/22/16 0:00	48.342915	-120.7003	392.4	River_or_stream	-116.17	-15.35	6.67	SPATIAL	98
17-040_7384	MMB200	8/22/16 0:00	48.334671	-120.69314	350.5	River_or_stream	-111.40	-15.17	9.98	SPATIAL	98
17-040_7387	MMB203	8/22/16 0:00	47.458426	-120.3326	189.1	River_or_stream	-106.14	-14.28	8.12	SPATIAL	98
17-040_7388	MMB204	8/22/16 0:00	47.425198	-120.3057	188.6	River_or_stream	-128.37	-16.86	6.48	SPATIAL	98
17-040_7391	MMB207	8/23/16 0:00	46.22213	-119.13844	103.7	River_or_stream	-128.24	-16.91	7.07	SPATIAL	98
17-040_7392	MMB208	8/23/16 0:00	46.0596	-118.90857	104.3	River_or_stream	-120.01	-15.47	3.75	SPATIAL	98
17-040_7394	MMB210	8/23/16 0:00	46.318185	-117.98267	488.6	River_or_stream	-108.18	-14.63	8.89	SPATIAL	98
17-040_7396	MMB212	8/24/16 0:00	46.363189	-117.06056	225.7	River_or_stream	-117.66	-14.79	0.65	SPATIAL	98
711132	Moses Lake	9/4/07 0:00	47.1844144	-119.36398	320.11	Lake	-117.48	-14.58	-0.82	EPA_Corvallis	10
CK 4204	Okanogan River At Malott	8/14/86 0:00	48.28055	-119.703	240.79	River_or_stream	-109.90	-13.27	-3.74	USGS	48
CK 4205	Okanogan River At Malott	10/6/86 0:00	48.28055	-119.703	240.79	River_or_stream	-109.30	-13.24	-3.38	USGS	48
CK 4201	Okanogan River At Malott	2/4/85 0:00	48.28055	-119.703	240.79	River_or_stream	-118.50	-14.60	-1.70	USGS	48

CK_4203	Okanogan River At Malott	8/5/85 0:00	48.28055	-119.703	240.79	River_or_stream	-117.60	-14.69	-0.08	USGS	48
CK_4200	Okanogan River At Malott	10/17/84 0:00	48.28055	-119.703	240.79	River_or_stream	-116.50	-14.70	1.10	USGS	48
CK_4206	Okanogan River At Malott	10/8/86 0:00	48.28055	-119.703	240.79	River_or_stream	-115.60	-14.61	1.28	USGS	48
CK_4209	Okanogan River At Malott	8/6/87 0:00	48.28055	-119.703	240.79	River_or_stream	-113.60	-14.36	1.28	USGS	48
CK_4207	Okanogan River At Malott	2/3/87 0:00	48.28055	-119.703	240.79	River_or_stream	-118.20	-15.07	2.36	USGS	48
CK_4202	Okanogan River At Malott	6/6/85 0:00	48.28055	-119.703	240.79	River_or_stream	-123.60	-16.36	7.28	USGS	48
CK_4208	Okanogan River At Malott	6/17/87 0:00	48.28055	-119.703	240.79	River_or_stream	-118.70	-15.78	7.54	USGS	48
NRSA0809-1888	Peshastin Creek	7/16/08 0:00	47.4628839	-120.66107		River_or_stream	-114.81	-15.03	5.46	EPA	165
NRSA0809-2252	Peshastin Creek	9/28/09 0:00	47.4628839	-120.66107		River_or_stream	-114.10	-15.53	10.17	EPA	165
711214	Red Rock Lake	9/12/07 0:00	46.8713894	-119.57087	210.96	Lake	-123.02	-15.75	2.99	EPA_Corvallis	10
711242	Saddle Mountain Lake	9/13/07 0:00	46.6934672	-119.64832	149.07	Lake	-111.43	-13.57	-2.89	EPA_Corvallis	10
CK_4401	Snake River At Burbank	3/11/87 0:00	46.21638	-119.0228		River_or_stream	-127.60	-16.44	3.92	USGS	48
CK_4403	Snake River At Burbank	8/19/87 0:00	46.21638	-119.0228		River_or_stream	-119.70	-15.63	5.34	USGS	48
CK_4395	Snake River At Burbank	11/26/85 0:00	46.21638	-119.0228		River_or_stream	-121.90	-15.95	5.70	USGS	48
CK_4400	Snake River At Burbank	11/10/86 0:00	46.21638	-119.0228		River_or_stream	-123.20	-16.12	5.76	USGS	48
CK_4393	Snake River At Burbank	2/9/85 0:00	46.21638	-119.0228		River_or_stream	-125.00	-16.40	6.20	USGS	48
CK_4402	Snake River At Burbank	4/28/87 0:00	46.21638	-119.0228		River_or_stream	-122.30	-16.09	6.42	USGS	48
CK_4396	Snake River At Burbank	3/10/86 0:00	46.21638	-119.0228		River_or_stream	-122.20	-16.10	6.60	USGS	48
CK_4392	Snake River At Burbank	11/19/84 0:00	46.21638	-119.0228		River_or_stream	-122.00	-16.15	7.20	USGS	48
CK_4397	Snake River At Burbank	5/8/86 0:00	46.21638	-119.0228		River_or_stream	-124.60	-16.48	7.24	USGS	48

CK_4399	Snake River At Burbank	8/12/86 0:00	46.21638	-119.0228		River_or_stream	-122.70	-16.38	8.34	USGS	48
CK_4398	Snake River At Burbank	5/28/86 0:00	46.21638	-119.0228		River_or_stream	-123.20	-16.47	8.56	USGS	48
CK_4394	Snake River At Burbank	5/21/85 0:00	46.21638	-119.0228		River_or_stream	-123.10	-16.70	10.50	USGS	48
NRSA0809- 1906	Snake River near Granite Dam	9/25/09 0:00	46.6559853	- 117.41411		River_or_stream	-122.30	-15.83	4.37	EPA	165
	Snake River near Granite Dam		46.6559853	- 117.41411		Stream/River	-122.30	-15.83	4.37	EPA	165
NRSA0809- 1908	Spokane River	9/9/08 0:00	47.6798164	- 117.21719		River_or_stream	-110.13	-14.82	8.41	EPA	165
CK_4194	Spokane River At Long Lake	9/4/85 0:00	47.83833	-117.8514	395.94	River_or_stream	-112.30	-14.67	5.06	USGS	48
CK_4189	Spokane River At Long Lake	9/13/84 0:00	47.83833	-117.8514	395.94	River_or_stream	-110.00	-14.40	5.20	USGS	48
CK_4199	Spokane River At Long Lake	9/2/86 0:00	47.83833	-117.8514	395.94	River_or_stream	-109.90	-14.52	6.26	USGS	48
CK_4193	Spokane River At Long Lake	7/10/85 0:00	47.83833	-117.8514	395.94	River_or_stream	-111.70	-14.79	6.62	USGS	48
CK_4190	Spokane River At Long Lake	11/15/84 0:00	47.83833	-117.8514	395.94	River_or_stream	-109.00	-14.50	7.00	USGS	48
CK_4195	Spokane River At Long Lake	11/21/85 0:00	47.83833	-117.8514	395.94	River_or_stream	-110.80	-14.74	7.12	USGS	48
CK_4196	Spokane River At Long Lake	1/13/86 0:00	47.83833	-117.8514	395.94	River_or_stream	-110.50	-14.77	7.66	USGS	48
CK_4197	Spokane River At Long Lake	3/5/86 0:00	47.83833	-117.8514	395.94	River_or_stream	-111.00	-14.88	8.04	USGS	48
CK_4198	Spokane River At Long Lake	7/17/86 0:00	47.83833	-117.8514	395.94	River_or_stream	-109.30	-14.67	8.06	USGS	48
CK_4191	Spokane River At Long Lake	1/16/85 0:00	47.83833	-117.8514	395.94	River_or_stream	-111.00	-14.90	8.20	USGS	48
CK_4192	Spokane River At Long Lake	5/28/85 0:00	47.83833	-117.8514	395.94	River_or_stream	-110.40	-15.02	9.76	USGS	48
NRSA0809- 1895	Touchet River	7/23/08 0:00	46.2761707	- 118.19248		River_or_stream	-106.73	-14.32	7.83	EPA	165

NRSA0809-1899	Trail Lake Coulee	8/19/08 0:00	47.5038301	-	119.29244		River_or_stream	-125.02	-16.29	5.28	EPA	165
NRSA0809-1887	Twentyfive Mile Creek	8/13/08 0:00	47.934476	-	120.30671		River_or_stream	-125.57	-17.01	10.52	EPA	165
NRSA0809-1918	Unnamed Tributary near Mount Spokane	7/21/09 0:00	47.9474663	-	117.10503		River_or_stream	-114.76	-15.68	10.65	EPA	165
NRSA0809-1578	Wanatchee River	7/27/09 0:00	47.6919568	-	120.71093		River_or_stream	-112.50	-15.18	8.93	EPA	165
NRSA0809-1910	Yakima River	10/22/09 0:00	46.4044218	-	120.28959		River_or_stream	-99.38	-13.48	8.46	EPA	165
CK_4253	Yakima River Abv Ahtanum Cr At Union Gap	9/17/85 0:00	46.53444	-120.4661	274.32		River_or_stream	-100.60	-13.41	6.68	USGS	48
CK_4262	Yakima River Abv Ahtanum Cr At Union Gap	8/11/87 0:00	46.53444	-120.4661	274.32		River_or_stream	-97.60	-13.05	6.80	USGS	48
CK_4263	Yakima River Abv Ahtanum Cr At Union Gap	9/10/87 0:00	46.53444	-120.4661	274.32		River_or_stream	-98.00	-13.11	6.88	USGS	48
CK_4254	Yakima River Abv Ahtanum Cr At Union Gap	11/5/85 0:00	46.53444	-120.4661	274.32		River_or_stream	-99.90	-13.38	7.14	USGS	48
CK_4255	Yakima River Abv Ahtanum Cr At Union Gap	1/27/86 0:00	46.53444	-120.4661	274.32		River_or_stream	-105.70	-14.13	7.34	USGS	48
CK_4250	Yakima River Abv Ahtanum Cr At Union Gap	3/13/85 0:00	46.53444	-120.4661	274.32		River_or_stream	-106.00	-14.20	7.60	USGS	48
CK_4258	Yakima River Abv Ahtanum Cr At Union Gap	11/5/86 0:00	46.53444	-120.4661	274.32		River_or_stream	-102.30	-13.79	8.02	USGS	48
CK_4248	Yakima River Abv Ahtanum Cr At Union Gap	11/8/84 0:00	46.53444	-120.4661	274.32		River_or_stream	-103.00	-13.90	8.20	USGS	48
CK_4261	Yakima River Abv Ahtanum Cr At Union Gap	5/14/87 0:00	46.53444	-120.4661	274.32		River_or_stream	-103.90	-14.08	8.74	USGS	48
CK_4249	Yakima River Abv Ahtanum	1/8/85 0:00	46.53444	-120.4661	274.32		River_or_stream	-103.50	-14.05	8.90	USGS	48

	Cr At Union Gap										
CK_4257	Yakima River Abv Ahtanum Cr At Union Gap	9/22/86 0:00	46.53444	-120.4661	274.32	River_or_stream	-98.80	-13.48	9.04	USGS	48
CK_4259	Yakima River Abv Ahtanum Cr At Union Gap	2/6/87 0:00	46.53444	-120.4661	274.32	River_or_stream	-103.40	-14.06	9.08	USGS	48
CK_4260	Yakima River Abv Ahtanum Cr At Union Gap	3/25/87 0:00	46.53444	-120.4661	274.32	River_or_stream	-104.20	-14.16	9.08	USGS	48
CK_4256	Yakima River Abv Ahtanum Cr At Union Gap	5/10/86 0:00	46.53444	-120.4661	274.32	River_or_stream	-103.70	-14.24	10.22	USGS	48
CK_4252	Yakima River Abv Ahtanum Cr At Union Gap	7/15/85 0:00	46.53444	-120.4661	274.32	River_or_stream	-100.60	-13.98	11.24	USGS	48
CK_4251	Yakima River Abv Ahtanum Cr At Union Gap	5/8/85 0:00	46.53444	-120.4661	274.32	River_or_stream	-104.80	-14.53	11.44	USGS	48
CK_4247	Yakima River Abv Ahtanum Cr At Union Gap	9/11/84 0:00	46.53444	-120.4661	274.32	River_or_stream	-100.00	-13.95	11.60	USGS	48
NRSA0809-1903	Yakima River at Benton	7/22/08 0:00	46.2711703	-119.57047		River_or_stream	-101.64	-13.53	6.58	EPA	165
CK_4281	Yakima River At Kiona	9/15/87 0:00	46.25361	-119.4769	138.5	River_or_stream	-100.70	-13.22	5.06	USGS	48
CK_4280	Yakima River At Kiona	8/20/87 0:00	46.25361	-119.4769	138.5	River_or_stream	-99.30	-13.15	5.90	USGS	48
CK_4273	Yakima River At Kiona	3/11/86 0:00	46.25361	-119.4769	138.5	River_or_stream	-110.30	-14.54	6.02	USGS	48
CK_4272	Yakima River At Kiona	1/8/86 0:00	46.25361	-119.4769	138.5	River_or_stream	-105.10	-13.99	6.82	USGS	48
CK_4266	Yakima River At Kiona	1/21/85 0:00	46.25361	-119.4769	138.5	River_or_stream	-105.00	-14.00	7.00	USGS	48
CK_4275	Yakima River At Kiona	9/15/86 0:00	46.25361	-119.4769	138.5	River_or_stream	-100.40	-13.45	7.20	USGS	48
CK_4276	Yakima River At Kiona	11/4/86 0:00	46.25361	-119.4769	138.5	River_or_stream	-102.70	-13.80	7.70	USGS	48
CK_4270	Yakima River At Kiona	9/11/85 0:00	46.25361	-119.4769	138.5	River_or_stream	-99.70	-13.43	7.74	USGS	48

CK_4267	Yakima River At Kiona	3/11/85 0:00	46.25361	-119.4769	138.5	River_or_stream	-106.50	-14.30	7.90	USGS	48
CK_4269	Yakima River At Kiona	7/10/85 0:00	46.25361	-119.4769	138.5	River_or_stream	-102.70	-13.83	7.94	USGS	48
CK_4279	Yakima River At Kiona	5/21/87 0:00	46.25361	-119.4769	138.5	River_or_stream	-101.60	-13.71	8.08	USGS	48
CK_4277	Yakima River At Kiona	1/20/87 0:00	46.25361	-119.4769	138.5	River_or_stream	-104.60	-14.10	8.20	USGS	48
CK_4278	Yakima River At Kiona	3/19/87 0:00	46.25361	-119.4769	138.5	River_or_stream	-106.90	-14.41	8.38	USGS	48
CK_4274	Yakima River At Kiona	7/1/86 0:00	46.25361	-119.4769	138.5	River_or_stream	-101.20	-13.70	8.40	USGS	48
CK_4271	Yakima River At Kiona	11/15/85 0:00	46.25361	-119.4769	138.5	River_or_stream	-99.60	-13.56	8.88	USGS	48
CK_4265	Yakima River At Kiona	11/20/84 0:00	46.25361	-119.4769	138.5	River_or_stream	-102.00	-13.95	9.60	USGS	48
CK_4268	Yakima River At Kiona	5/1/85 0:00	46.25361	-119.4769	138.5	River_or_stream	-102.50	-14.16	10.78	USGS	48
CK_4264	Yakima River At Kiona	9/10/84 0:00	46.25361	-119.4769	138.5	River_or_stream	-101.00			USGS	48

Appendix C. Meteoric waters for windward lapse rate determination (WaterIsotopes, 2020; IAEA, 2020).

Sample ID	Site Name	Collection Date	Latitude	Longitude	Collection Elevation (mabsl)	Collection Elevation from Google Earth (m)	Type	δD (per mille)	$\delta^{18}O$ (per mille)	d	WI Analysis Source	Project ID
711059	Lewis Lake	8/29/07 0:00	46.98630288	-122.5690307	108.21	107	Lake	-38.43	-2.94	-14.91	EPA_Corvallis	10
711054	Swamp	8/28/07 0:00	47.31108363	-121.2990598	732.43	734	Lake	-72.53	-8.24	-6.61	EPA_Corvallis	10
710974	U Lake	8/21/07 0:00	47.427764	-123.074122	144.98	148	Lake	-50.93	-5.61	-6.08	EPA_Corvallis	10
710719	Forbes Lake	8/7/07 0:00	47.19204698	-122.9725593	30.04	30	Lake	-50.05	-5.82	-3.52	EPA_Corvallis	10
710935	American Lake	8/21/07 0:00	47.13285576	-122.5619208	72.65	71	Lake	-57.73	-6.90	-2.56	EPA_Corvallis	10
711006	Koeneman Lake	8/24/07 0:00	47.40930776	-122.7843969	63.56	66	Lake	-58.45	-7.16	-1.13	EPA_Corvallis	10
710204	Swofford Pond	7/5/07 0:00	46.49728658	-122.4056376	238.87	241	Lake	-64.99	-8.28	1.25	EPA_Corvallis	10
17-040_7365	MMB181	8/20/16 0:00	46.911352	-121.657698	1889.3	1891	Lake	100.61	-12.90	2.59	SPATIAL	98
17-040_7351	MMB167	8/19/16 0:00	46.978325	-123.883273	1.1	1	Stream/River	-27.33	-3.85	3.45	SPATIAL	98
710376	Swamp	7/17/07 0:00	47.31108363	-121.2990598	732.43	734	Lake	-81.33	-10.68	4.09	EPA_Corvallis	10

17-040_7353	MMB169	8/19/16 0:00	46.977018	-123.796332	2.5	2	Stream/River	-36.89	-5.27	5.28	SPATIAL	98
CK_4021	Willapa River Near Willapa	5/23/85 0:00	46.64999	-123.6528	1.0973	7	Stream/River	-58.9	-8.75	11.10	USGS	48
CK_4024	Willapa River Near Willapa	3/6/86 0:00	46.64999	-123.6528	1.0973	7	Stream/River	-60.1	-8.72	9.66	USGS	48
CK_4020	Willapa River Near Willapa	3/21/85 0:00	46.64999	-123.6528	1.0973	7	Stream/River	-60	-8.7	9.60	USGS	48
CK_4025	Willapa River Near Willapa	5/29/86 0:00	46.64999	-123.6528	1.0973	7	Stream/River	-58.1	-8.61	10.78	USGS	48
CK_4019	Willapa River Near Willapa	11/16/84 0:00	46.64999	-123.6528	1.0973	7	Stream/River	-59.5	-8.55	8.90	USGS	48
CK_4023	Willapa River Near Willapa	11/15/85 0:00	46.64999	-123.6528	1.0973	7	Stream/River	-57	-8.5	11.00	USGS	48
CK_4022	Willapa River Near Willapa	8/21/85 0:00	46.64999	-123.6528	1.0973	7	Stream/River	-57.7	-8.29	8.62	USGS	48
CK_4026	Willapa River Near Willapa	8/28/86 0:00	46.64999	-123.6528	1.0973	7	Stream/River	-55.9	-8	8.10	USGS	48
CK_4029	Chehalis River At Porter	1/28/85 0:00	46.93804	-123.3125	7.1933	9	Stream/River	-67	-9.65	10.20	USGS	48
CK_4035	Chehalis River At Porter	1/23/86 0:00	46.93804	-123.3125	7.1933	9	Stream/River	-65.8	-9.6	11.00	USGS	48
CK_4036	Chehalis River At Porter	3/24/86 0:00	46.93804	-123.3125	7.1933	9	Stream/River	-66.1	-9.52	10.06	USGS	48
CK_4030	Chehalis River At Porter	3/18/85 0:00	46.93804	-123.3125	7.1933	9	Stream/River	-67	-9.5	9.00	USGS	48
CK_4031	Chehalis River At Porter	5/20/85 0:00	46.93804	-123.3125	7.1933	9	Stream/River	-64.5	-9.5	11.50	USGS	48
CK_4037	Chehalis River At Porter	5/30/86 0:00	46.93804	-123.3125	7.1933	9	Stream/River	-64.3	-9.48	11.54	USGS	48
CK_4039	Chehalis River At Porter	1/27/87 0:00	46.93804	-123.3125	7.1933	9	Stream/River	-63.5	-9.36	11.38	USGS	48

CK_4028	Chehalis River At Porter	11/16/84 0:00	46.93804	-123.3125	7.1933	9	Stream/River	-65.5	-9.35	9.30	USGS	48
CK_4027	Chehalis River At Porter	9/20/84 0:00	46.93804	-123.3125	7.1933	9	Stream/River	-64	-9.35	10.80	USGS	48
CK_4034	Chehalis River At Porter	11/12/85 0:00	46.93804	-123.3125	7.1933	9	Stream/River	-63.5	-9.34	11.22	USGS	48
CK_4033	Chehalis River At Porter	9/23/85 0:00	46.93804	-123.3125	7.1933	9	Stream/River	-62.8	-9.32	11.76	USGS	48
CK_4040	Chehalis River At Porter	5/6/87 0:00	46.93804	-123.3125	7.1933	9	Stream/River	-64.5	-9.26	9.58	USGS	48
CK_4038	Chehalis River At Porter	7/22/86 0:00	46.93804	-123.3125	7.1933	9	Stream/River	-63.6	-9.21	10.08	USGS	48
CK_4032	Chehalis River At Porter	7/22/85 0:00	46.93804	-123.3125	7.1933	9	Stream/River	-63.4	-9.14	9.72	USGS	48
CK_4042	Chehalis River At Porter	9/10/87 0:00	46.93804	-123.3125	7.1933	9	Stream/River	-62.8	-9.1	10.00	USGS	48
CK_4041	Chehalis River At Porter	7/8/87 0:00	46.93804	-123.3125	7.1933	9	Stream/River	-64.2	-9.07	8.36	USGS	48
17-040_7354	MMB170	8/19/16 0:00	46.999313	-123.492539	12.6	8	Stream/River	-59.83	-8.62	9.10	SPATIAL	98
17-040_7346	MMB162	8/18/16 0:00	47.467764	-123.847034	68	68	Lake	-72.46	-10.39	10.62	SPATIAL	98
17-040_7345	MMB161	8/18/16 0:00	47.464312	-123.842423	90.1	94	Stream/River	-60.79	-9.04	11.52	SPATIAL	98
17-040_7357	MMB173	8/19/16 0:00	46.531968	-122.558116	130.5	130	Lake	-77.71	-10.76	8.36	SPATIAL	98
711198	Cushman Lake	9/11/07 0:00	47.48799465	123.2647195	225.08	222	Lake	-75.42	-10.71	10.27	EPA Corvallis	10
17-040_7358	MMB174	8/19/16 0:00	46.534867	-121.794237	285.9	286	Stream/River	-96.27	-13.32	10.25	SPATIAL	98
17-040_7369	MMB185	8/20/16 0:00	47.158447	-121.65803	512	515	Stream/River	-91.66	-12.70	9.94	SPATIAL	98
710819	Cle Elum Lake	8/14/07 0:00	47.26690206	-121.094003	678.81	681	Lake	-97.19	-13.10	7.64	EPA Corvallis	10
17-040_7363	MMB179	8/20/16 0:00	46.766528	-121.789606	963.4	965	Stream/River	106.18	-14.70	11.38	SPATIAL	98
17-040_7368	MMB184	8/20/16 0:00	46.902765	-121.629282	1245	1245	Stream/River	120.45	-16.34	10.24	SPATIAL	98
17-040_7364	MMB180	8/20/16 0:00	46.768778	-121.731565	1481.9	1482	Lake	-89.33	-12.11	7.53	SPATIAL	98

17-040_7362	MMB178	8/19/16 0:00	46.790215	-121.726761	1599.6	1600	Stream/River	-94.38	-12.93	9.05	SPATIAL	98
17-040_7361	MMB177	8/19/16 0:00	46.791536	-121.732688	1702.7	1704	Stream/River	-93.15	-12.93	10.28	SPATIAL	98
17-040_7367	MMB183	8/20/16 0:00	46.919123	-121.665766	2049.9	2050	Lake	-	-13.68	7.48	SPATIAL	98
NRSA0809-1911	Rattlesnake Creek	9/17/08 0:00	46.79931424	-		859	Stream/River	108.07	-14.63	8.96	EPA	165
NRSA0809-1914	Cle Elum River	8/18/09 0:00	47.42374197	-		789	Stream/River	105.51	-14.58	11.11	EPA	165
CK_4080	Puyallup River At Puyallup	8/5/86 0:00	47.21444	-122.3403		7	Stream/River	-	-14.14	11.12	USGS	48
CK_4076	Puyallup River At Puyallup	8/19/85 0:00	47.21444	-122.3403		7	Stream/River	-	-14.13	9.54	USGS	48
CK_4081	Puyallup River At Puyallup	8/26/87 0:00	47.21444	-122.3403		7	Stream/River	-	-13.94	11.32	USGS	48
CK_4075	Puyallup River At Puyallup	5/13/85 0:00	47.21444	-122.3403		7	Stream/River	-84.90	-12.20	12.70	USGS	48
NRSA0809-1885	Rushing Water Creek	9/15/09 0:00	46.896298	-		670	Stream/River	-85.00	-11.86	9.88	EPA	165
CK_4073	Puyallup River At Puyallup	11/26/84 0:00	47.21444	-122.3403		7	Stream/River	-85.00	-11.65	8.20	USGS	48
CK_4074	Puyallup River At Puyallup	3/4/85 0:00	47.21444	-122.3403		7	Stream/River	-85.00	-11.60	7.80	USGS	48
CK_4078	Puyallup River At Puyallup	2/19/86 0:00	47.21444	-122.3403		7	Stream/River	-82.50	-11.54	9.82	USGS	48
CK_4077	Puyallup River At Puyallup	11/19/85 0:00	47.21444	-122.3403		7	Stream/River	-81.50	-11.50	10.50	USGS	48
CK_4079	Puyallup River At Puyallup	5/19/86 0:00	47.21444	-122.3403		7	Stream/River	-80.30	-11.24	9.62	USGS	48
NRSA0809-1896	Kiona Creek	7/29/09 0:00	46.5377567	-		316	Stream/River	-79.26	-11.19	10.23	EPA	165
NRSA0809-1890	Medicine Creek	7/30/09 0:00	47.05149107	-		4	Stream/River	-70.33	-9.59	6.39	EPA	165
NRSA0809-1913	East Fork Hoquiam River	7/28/09 0:00	47.06727475	-		17	Stream/River	-55.29	-8.26	10.78	EPA	165
NRSA0809-1919	Wishkah River	10/6/09 0:00	47.13550231	-		30	Stream/River	-56.79	-8.14	8.36	EPA	165

NRSA0809-1898	Unnamed south of Oakville	9/9/09 0:00	46.8375725	-123.3862738		167	Stream/River	-57.26	-8.12	7.67	EPA	165
NRSA0809-1915	Williams Creek	10/11/09 0:00	46.53201333	-123.8270244		120	Stream/River	-50.13	-7.65	11.06	EPA	165

Appendix D. Meteoric waters used in the determination for the leeward lapse rate (WaterIsotopes, 2020; IAEA, 2020).

Sample ID	Site Name	Collection Date	Latitude	Longitude	Collection Elevation (mabsl)	Collection Elevation from Google Earth (m)	Type	δD (per mille)	$\delta^{18}O$ (per mille)	d	WI Analysis Source	Project ID
710866	Grimes	8/16/07 0:00	47.7286971	-119.5926	559.3	559	Lake	-73.58	-5.10	-32.78	EPA_Corvallis	10
711100	Medical Lake	8/30/07 0:00	47.5706872	-117.68899	731.2	730	Lake	-61.57	-4.19	-28.05	EPA_Corvallis	10
711242	Saddle Mountain Lake	9/13/07 0:00	46.6934672	-119.64832	149.1	149	Lake	-111.43	-13.57	-2.89	EPA_Corvallis	10
711132	Moses Lake	9/4/07 0:00	47.1844144	-119.36398	320.1	318	Lake	-117.48	-14.58	-0.82	EPA_Corvallis	10
CK_4224	Columbia R At Vernita Br Nr Priest Rpds Dm	9/30/85 0:00	46.63999	-119.7317		121	Stream/River	-132.60	-16.74	1.32	USGS	48
711214	Red Rock Lake	9/12/07 0:00	46.8713894	-119.57087	211	210	Lake	-123.02	-15.75	2.99	EPA_Corvallis	10
NRSA0809-1906	Snake River near Granite Dam	9/25/09 0:00	46.6559853	-117.41411		225	Stream/River	-122.30	-15.83	4.37	EPA	165
CK_4225	Columbia R At Vernita Br Nr Priest Rpds Dm	12/17/85 0:00	46.63999	-119.7317		121	Stream/River	-132.30	-17.17	5.06	USGS	48
CK_4234	Columbia R At Vernita Br Nr Priest Rpds Dm	5/19/87 0:00	46.63999	-119.7317		121	Stream/River	-126.00	-16.54	6.32	USGS	48
CK_4220	Columbia R At Vernita Br Nr Priest Rpds Dm	1/22/85 0:00	46.63999	-119.7317		121	Stream/River	-134.00	-17.55	6.40	USGS	48
17-040_7388	MMB204	8/22/16 0:00	47.425198	-120.3057	188.6	188	Stream/River	-128.37	-16.86	6.48	SPATIAL	98

CK_4231	Columbia R At Vernita Br Nr Priest Rpds Dm	11/12/86 0:00	46.63999	-119.7317		121	Stream/River	-131.50	-17.26	6.58	USGS	48
CK_4253	Yakima River Abv Ahtanum Cr At Union Gap	9/17/85 0:00	46.53444	-120.4661	274.3	289	Stream/River	-100.60	-13.41	6.68	USGS	48
CK_4262	Yakima River Abv Ahtanum Cr At Union Gap	8/11/87 0:00	46.53444	-120.4661	274.3	289	Stream/River	-97.60	-13.05	6.80	USGS	48
CK_4263	Yakima River Abv Ahtanum Cr At Union Gap	9/10/87 0:00	46.53444	-120.4661	274.3	289	Stream/River	-98.00	-13.11	6.88	USGS	48
CK_4218	Columbia R At Vernita Br Nr Priest Rpds Dm	9/11/84 0:00	46.63999	-119.7317		121	Stream/River	-129.50	-17.05	6.90	USGS	48
CK_4221	Columbia R At Vernita Br Nr Priest Rpds Dm	3/26/85 0:00	46.63999	-119.7317		121	Stream/River	-137.50	-18.05	6.90	USGS	48
17-040_7324	MMB140	8/12/16 0:00	46.941122	-119.98422	175.2	175	Lake	-128.91	-16.99	6.97	SPATIAL	98
CK_4254	Yakima River Abv Ahtanum Cr At Union Gap	11/5/85 0:00	46.53444	-120.4661	274.3	289	Stream/River	-99.90	-13.38	7.14	USGS	48
CK_4226	Columbia R At Vernita Br Nr Priest Rpds Dm	1/21/86 0:00	46.63999	-119.7317		121	Stream/River	-133.30	-17.56	7.18	USGS	48
CK_4255	Yakima River Abv Ahtanum Cr At Union Gap	1/27/86 0:00	46.53444	-120.4661	274.3	289	Stream/River	-105.70	-14.13	7.34	USGS	48
CK_4219	Columbia R At Vernita Br Nr Priest Rpds Dm	11/14/84 0:00	46.63999	-119.7317		121	Stream/River	-131.00	-17.30	7.40	USGS	48
CK_4229	Columbia R At Vernita Br Nr Priest Rpds Dm	7/21/86 0:00	46.63999	-119.7317		121	Stream/River	-127.50	-16.88	7.54	USGS	48
CK_4233	Columbia R At Vernita Br Nr Priest Rpds Dm	3/10/87 0:00	46.63999	-119.7317		121	Stream/River	-133.80	-17.67	7.56	USGS	48
CK_4227	Columbia R At Vernita Br Nr Priest Rpds Dm	3/12/86 0:00	46.63999	-119.7317		121	Stream/River	-133.70	-17.66	7.58	USGS	48
CK_4230	Columbia R At Vernita Br Nr Priest Rpds Dm	9/25/86 0:00	46.63999	-119.7317		121	Stream/River	-132.40	-17.50	7.60	USGS	48
CK_4250	Yakima River Abv Ahtanum Cr At Union Gap	3/13/85 0:00	46.53444	-120.4661	274.3	289	Stream/River	-106.00	-14.20	7.60	USGS	48

CK_4236	Columbia R At Vernita Br Nr Priest Rpds Dm	9/2/87 0:00	46.63999	-119.7317		121	Stream/River	- 130.3 0	-17.25	7.70	USGS	48
CK_4232	Columbia R At Vernita Br Nr Priest Rpds Dm	1/21/87 0:00	46.63999	-119.7317		121	Stream/River	- 130.8 0	-17.35	8.00	USGS	48
CK_4258	Yakima River Abv Ahtanum Cr At Union Gap	11/5/86 0:00	46.53444	-120.4661	274.3	289	Stream/River	- 102.3 0	-13.79	8.02	USGS	48
CK_4235	Columbia R At Vernita Br Nr Priest Rpds Dm	7/7/87 0:00	46.63999	-119.7317		121	Stream/River	- 125.8 0	-16.73	8.04	USGS	48
CK_4222	Columbia R At Vernita Br Nr Priest Rpds Dm	5/28/85 0:00	46.63999	-119.7317		121	Stream/River	- 126.0 0	-16.76	8.08	USGS	48
17- 040_7387	MMB203	8/22/16 0:00	47.458426	-120.3326	189.1	189	Stream/River	- 106.1 4	-14.28	8.12	SPATIAL	98
CK_4223	Columbia R At Vernita Br Nr Priest Rpds Dm	7/29/85 0:00	46.63999	-119.7317		121	Stream/River	- 126.9 0	-16.88	8.14	USGS	48
CK_4248	Yakima River Abv Ahtanum Cr At Union Gap	11/8/84 0:00	46.53444	-120.4661	274.3	289	Stream/River	- 103.0 0	-13.90	8.20	USGS	48
17- 040_7327	MMB143	8/12/16 0:00	46.978086	- 120.56742	458.2	456	Stream/River	-94.91	-12.96	8.73	SPATIAL	98
CK_4261	Yakima River Abv Ahtanum Cr At Union Gap	5/14/87 0:00	46.53444	-120.4661	274.3	289	Stream/River	- 103.9 0	-14.08	8.74	USGS	48
CK_4228	Columbia R At Vernita Br Nr Priest Rpds Dm	5/27/86 0:00	46.63999	-119.7317		121	Stream/River	- 125.3 0	-16.76	8.78	USGS	48
CK_4249	Yakima River Abv Ahtanum Cr At Union Gap	1/8/85 0:00	46.53444	-120.4661	274.3	289	Stream/River	- 103.5 0	-14.05	8.90	USGS	48
CK_4257	Yakima River Abv Ahtanum Cr At Union Gap	9/22/86 0:00	46.53444	-120.4661	274.3	289	Stream/River	-98.80	-13.48	9.04	USGS	48
CK_4259	Yakima River Abv Ahtanum Cr At Union Gap	2/6/87 0:00	46.53444	-120.4661	274.3	289	Stream/River	- 103.4 0	-14.06	9.08	USGS	48
CK_4260	Yakima River Abv Ahtanum Cr At Union Gap	3/25/87 0:00	46.53444	-120.4661	274.3	289	Stream/River	- 104.2 0	-14.16	9.08	USGS	48
CK_4256	Yakima River Abv Ahtanum Cr At Union Gap	5/10/86 0:00	46.53444	-120.4661	274.3	289	Stream/River	- 103.7 0	-14.24	10.22	USGS	48

CK_4252	Yakima River Abv Ahtanum Cr At Union Gap	7/15/85 0:00	46.53444	-120.4661	274.3	289	Stream/River	- 100.6 0	-13.98	11.24	USGS	48
CK_4251	Yakima River Abv Ahtanum Cr At Union Gap	5/8/85 0:00	46.53444	-120.4661	274.3	289	Stream/River	- 104.8 0	-14.53	11.44	USGS	48
CK_4247	Yakima River Abv Ahtanum Cr At Union Gap	9/11/84 0:00	46.53444	-120.4661	274.3	289	Stream/River	- 100.0 0	-13.95	11.60	USGS	48