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Evaluating the Efficacy of Manmade Canals at Maintaining Lake Habitats for Salmon and Birds Using Seasonal Variations in Isotopes of Meteoric Water

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Abstract

We investigated whether hydrologic restoration at Sturgeon Lake, Oregon, USA has sufficiently increased water flux and reduced stagnation, improving environmental conditions for juvenile salmon and waterfowl. This 19.2km^2 lake is a pivotal environmental feature in the area, providing a haven for salmon on the Columbia River before reaching the Pacific Ocean and winter habitat for hundreds of thousands of waterfowl and migratory birds on the Pacific Flyway. The Oregon Conservation Strategy names restoring natural hydrology to Sturgeon Lake as a key step toward conservation in this area. We use stable isotopes of water from the lake, surrounding water bodies, and precipitation to understand the restoration work's efficacy and whether further efforts are necessary to restore healthy habitats. Because of its importance to bird migration and salmon spawning, we focus on seasonal patterns in lake hydrology. We determined that approximately 36.5% and 9.5% of water input was lost to evaporation during the summer and winter, respectively, after restoration. We estimate the residence time of water in the lake to average ˜43.2 days during the study period. Based on these results, we determined that the lake habitat is being adequately maintained in the winter, when it is most valuable to local fauna, but that some stagnation and potential ecosystem degradation occurs in the summer. Neither juvenile salmonids nor migratory birds utilize the lake during the summer, therefore the restoration work is effective at maintaining habitat for these species, but further summer-focused work could be beneficial.

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Key Points:

- Canal connecting Columbia River to Sturgeon Lake is effectively maintaining salmon and migratory bird habitat during the winter.
- Sturgeon Lake experiences ecosystem degradation in the summer.
- Isotope hydrology methods are a practical and straightforward way to evaluate the efficacy of similar restoration canals.

Abstract

We investigated whether hydrologic restoration at Sturgeon Lake, Oregon, USA has sufficiently increased water flux and reduced stagnation, improving environmental conditions for juvenile salmon and waterfowl. This 19.2km^2 lake is a pivotal environmental feature in the area, providing a haven for salmon on the Columbia River before reaching the Pacific Ocean and winter habitat for hundreds of thousands of waterfowl and migratory birds on the Pacific Flyway. The Oregon Conservation Strategy names restoring natural hydrology to Sturgeon Lake as a key step toward conservation in this area. We use stable isotopes of water from the lake, surrounding water bodies, and precipitation to understand the restoration work's efficacy and whether further efforts are necessary to restore healthy habitats. Because of its importance to bird migration and salmon spawning, we focus on seasonal patterns in lake hydrology. We determined that approximately 36.5% and 9.5% of water input was lost to evaporation during the summer and winter, respectively, after restoration. We estimate the residence time of water in the lake to average ~43.2 days during the study period. Based on these results, we determined that the lake habitat is being adequately maintained in the winter, when it is most valuable to local fauna, but that some stagnation and potential ecosystem degradation occurs in the summer. Neither juvenile salmonids nor migratory birds utilize the lake during the summer, therefore the restoration work is effective at maintaining habitat for these species, but further summer-focused work could be beneficial.

Plain Language Summary

This article discusses the impacts of environmental restoration work focused on Sturgeon Lake, Oregon. We used water chemistry to determine whether a newly dredged canal connecting the lake with the Columbia River has been effective at maintaining the lake as a valuable habitat for native salmon and bird species. We found that a significant amount of water flows in and out of the lake during the winter, creating a healthy ecosystem for fauna which primarily use the lake in the winter. Thus, we conclude that restoration work has been effective, despite not maintaining the ecosystem in the summer when stagnation and evaporation is significant.

1 Introduction

1.1 Goals and motivation

This work evaluates the state of the Sturgeon Lake, Oregon USA ecosystem following restoration efforts performed by the West Multnomah Soil and Water Conservation District (WMSWCD). Restoration efforts aimed to reduce stagnation and ecosystem degradation by dredging a canal to increase inflow of water to the lake. Through stable isotope analysis of the lake and surrounding water bodies, we evaluate the magnitude of flushing flow to Sturgeon Lake, focusing on the following questions:

- What is the post-restoration residence time of Sturgeon Lake?
- Are flushing flows from the Dairy Creek canal sufficient to mitigate stagnation and contaminant buildup?
- Is further restoration work necessary to maintain this critical ecosystem?

Our initial hypothesis was that the canal dredged in 2018 to reconnect Sturgeon Lake to the Columbia River provides sufficient flushing flow to maintain the Sturgeon Lake ecosystem.

1.2 Background and context

1.2.1 Stable isotopes of meteoric water and applications to lake health

The isotopes employed here are oxygen-16 (^{16}O), oxygen-18 (^{18}O), hydrogen-1 (^{1}H), and hydrogen-2 (^{2}H, also called deuterium, D). The ratios $^{18}O/^{16}O$ and $^{2}H/^{1}H$ in meteoric water change as a function of hydrologic parameters, including lake residence time. These measurements allow us to constrain myriad aspects of the hydrologic cycle, including (but not limited to) evaporation amount, residence time, and source water (Criss, 1999).

Isotopic ratios evolve due to *fractionation*, a process by which heavy isotopes are concentrated in one phase while the relatively light isotopes become concentrated in another (Clark and Fritz, 1997). One example is water evaporation: when water evaporates, the lighter isotopes (^{16}O, ^{1}H) are preferentially incorporated into the water vapor, while the heavier isotopes (^{18}O, ^{2}H) concentrate in the remaining liquid water (Clark and Fritz, 1997). This process results in isotopic *enrichment* and *depletion*, where the liquid water becomes *enriched* in the heavy isotopes while the vapor becomes *depleted* in the heavy isotopes (Kendall and Caldwell, 1998). The phase which is enriched is typically the one with the higher bond strength: in a phase change sequence of H_2O from solid (ice), to liquid, to vapor, the solid would be most enriched and the vapor would be most depleted, provided some water remained in each phase (Kendall and Caldwell, 1998).

The use of stable isotopes of hydrogen and oxygen to estimate lake residence time and evaporation rates is well-established in the field of hydrology, as are these parameters' use in investigating the health of lake ecosystems (Gonfiantini, 1986; Brooks et al., 2014; Gibson et al., 2016). The primary issues pertaining to Sturgeon Lake health that have motivated hydrologic restoration efforts include sedimentation, bacteria and organic matter buildup, high concentrations of nutrients (phosphorus and nitrogen), algal blooms, and high concentrations of cyanobacteria (Klingeman, 1987; HDR Engineering, Inc., 2013). Directly correlated to these issues are the *throughflow index* (ratio of evaporation to inflow, E/I) and residence time of lake water, both of which can be constrained using stable isotope measurements (Brooks et al., 2014; Zanazzi et al., 2020). Typically, higher values of E/I coincide with increased nutrient concentration. Also, longer residence times may increase nutrient concentration, encourage sedimentation, and increase growth of cyanobacteria (Brooks et al., 2014; Zanazzi et al., 2020). Sturgeon Lake is also facing high potential for eutrophication and toxicity from deposition of heavy metals (Klingeman, 1987; HDR Engineering, Inc., 2013). Long residence times have been associated with increased sedimentation of heavy metals and increased risk of eutrophication (Schindler, 2006).

Generally, relatively high values of E/I ($> \sim 0.2$ for this region) are associated with poor lake ecosystem quality (Brooks et al., 2014). The United States Environmental Protection Agency (USEPA) National Lake Assessment, which focused on evaluating the quality of lake ecosystems in the U.S., created a model for lake ecosystem quality that allows us to use isotopic calculations of hydrologic parameters to infer the biological condition of lakes such as Sturgeon Lake (Brooks et al., 2014). In lakes evaluated using models within the USEPA survey, it has been shown that E/I is negatively correlated with biological conditions (i.e., higher E/I implies worse biological conditions). The correlation between residence time and biological condition is poorly understood, and the throughflow index is a more accepted and well-established indicator of lake health (Brooks et al., 2014). However, there is evidence that higher residence times are linked with improved lake health (Brooks et al., 2014), and it is clear that residence time impacts lake ecosystem quality, influencing sedimentation, heavy metal toxicity, and eutrophication.

1.2.2 Stable isotope analysis of meteoric water samples

The isotopic composition of water is typically measured using mass spectrometry or laser absorption spectroscopy and reported in *delta notation*, denoted with a Greek lowercase delta (δ). Delta values represent ratios of heavy to light isotopes (e.g., $^{18}O/^{16}O$) in a sample relative to a standard of known composition in parts-per-thousand (permille, ‰) (Kendall and Caldwell, 1998). Accurately measuring the absolute permille concentration of each isotope is very difficult—therefore, a delta value such as $\delta^{18}O$ represents the *difference* between the measurement of a sample and the measurement of a standard of known composition, which significantly reduces analytical error (Clark and Fritz, 1997). Typical 2σ errors in isotopic measurements are < 0.2‰ for $\delta^{18}O$ and < 1‰ for $\delta^{2}H$ (e.g., Bershaw et al., 2012). Commonly, laboratories have in-house standards that have been prepared with respect to the internationally recognized standard Vienna Standard Mean Ocean Water (VSMOW).

A negative delta value represents water depleted in ^{18}O or ^{2}H relative to VSMOW, whereas a positive delta value represents water enriched in ^{18}O or ^{2}H relative to VSMOW. Different sources of moisture may have unique isotopic compositions that can constrain the provenance of meteoric water samples (e.g., Tian et al., 2007; Cui et al., 2009; Bershaw, 2018).

1.2.3 Source water and meteoric water lines

Meteoric water lines are a key feature of many isotope hydrology studies, formed by plotting $\delta^{2}H$ as a function of $\delta^{18}O$ and observing the resulting linear relationship. Commonly, we use the Global Meteoric Water Line as a reference, a well-established model developed by plotting numerous delta values of meteoric water across the globe (Craig, 1961):

$$\delta^2 H = 8 \cdot \delta^{18} O + 10. \qquad Eq. 1$$

Using the measured values for δ^2H and $\delta^{18}O$, we can calculate the *deuterium excess* (d-excess). D-excess is a function of both δ^2H and $\delta^{18}O$, defined as:

$$\text{d-excess (‰)} = \delta^2 H - 8 \cdot \delta^{18} O. \qquad Eq. 2$$

In essence, d-excess represents the y-intercept of a line with slope 8.00 (from Equation 1) plotted in $\delta^{18}O$ (x), δ^2H (y) space.

By plotting isotopic measurements of local or regional data, we can generate a Local Meteoric Water Line (LMWL). The LMWL and GMWL can provide a good first-order estimate of whether a body has experienced significant levels of evaporation. If the LMWL has a slope below that of the GMWL, this is indicative evaporative enrichment. If the slope of a subset is lower than that of the LMWL, this indicates some level of evaporation beyond that which is common for the area (Rozanski et al., 1993).

1.2.4 Study Area

Sauvie Island is an 84.83km^2 river island located in both Multnomah and Columbia Counties, Oregon, bordered by the Willamette River to the south, the Multnomah Channel (an anastomosing channel of the Willamette) to the west, and the Columbia River to the east (Figure 1). The island is composed entirely of Quaternary floodplain deposits, consisting of gravels, sands, and muds that are 70-90m thick, facilitating groundwater storage and flow throughout the subsurface (Evarts et al., 2016). When the West Multnomah Soil & Water Conservation District (WMSWCD) was formed in 1944, they started working on the restoration of Sturgeon Lake, the largest lake on Sauvie Island. Sturgeon Lake exists on the northern half of the island, with a surface area of approximately 19.2km^2, an average depth of 1.2m (winter) and 4.6m (summer), and an average water volume of 2.3 x 10^7 m^3 (Ward and Rien, 1992). The lake primarily functions as a throughflow lake, being fed by the Columbia River through surface water from Dairy Creek and through Columbia River groundwater (Saslaw and Bershaw, 2018). Outflow of surface water is routed into the Multnomah Channel through the Gilbert River at the north end of the island, which empties back into the Columbia River downstream of the island.

According to the WMSWCD, a levee built by the U.S. Army Corps of Engineers (USACE) in 1941 drastically reduced the flow of surface water into Sturgeon Lake. This caused sediment accumulation within the lake and eventually led to the lake functioning primarily as an off-channel sediment basin for the Columbia and Willamette Rivers (Klingeman, 1987). Efforts by the WMSWCD, Oregon Department of Environmental Quality, and Oregon Department of Fish and Wildlife reconnected Sturgeon Lake to the Columbia River in 1989. However, historic flooding from 1996-97 blocked the manmade channel, inhibiting flow and causing additional degradation.

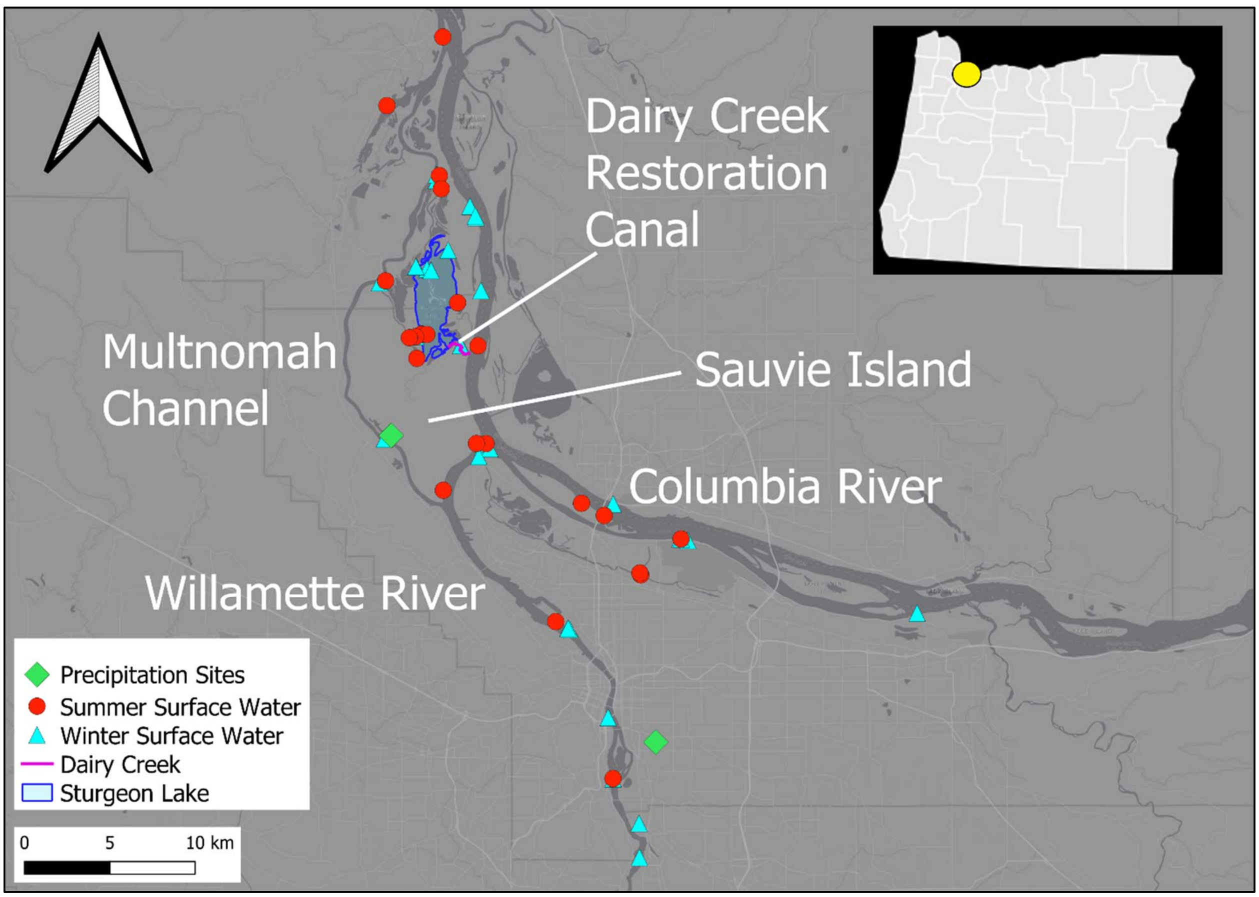

Figure 1. Overview of study area centered around Sauvie Island, OR. The Columbia River, Willamette River, and Multnomah Channel are each labeled, with Sturgeon Lake highlighted in blue and Dairy Creek traced in purple. The spatial distribution of water samples throughout the study area is also shown. Summer samples are symbolized with red circles, winter samples with light blue triangles, and precipitation collection sites with green diamonds.

Figure 2. View of Sturgeon Lake.

In 2007, the USACE conducted a study in the area and recommended replacing failing culverts along Dairy Creek (the lake's main inlet) with a full-spanning bridge, removing a sand plug from the mouth of dairy creek, and modifying the channel morphology (WMSWCD, 2020). The WMSWCD, in conjunction with the USEPA and USACE, named a lack of flushing flow as the "critical problem" that the lake was facing. Data collected from 1980-86 showed that, without action, the lake would continue to face ecological degradation and overall reduction in size due to high levels of bacteria buildup and net sedimentation, respectively. The specific causes of hazardous levels of coliform bacteria are unknown (Klingeman, 1987). The goal of restoration and construction was to increase the flux of water from the Columbia River into the lake. The project also constructed a low flow channel designed to allow fish passage to and from Sturgeon Lake through Dairy Creek in the summer months, though this is primarily for the benefit of nonnative, warm-water fish which are not necessarily the focus of these restoration efforts (WMSWCD, 2020).

Sturgeon Lake's significance as a wildlife habitat and recreational attraction makes it a continued focus for restoration efforts. The Oregon Conservation Strategy (OCS) specifically names three initiatives that are directly related to this study:

- "Maintain wetlands and open water areas for the benefit of waterfowl, shorebirds, turtles, amphibians, and bats."
- "Re-establish natural hydrology."
- "Re-establish juvenile salmon rearing areas" (Hanson et al., 2016).

The OCS also names this area as one of the most important stopovers in the Pacific Flyway, a migratory bird path from South America to Alaska. Indeed, some 200,000 geese alone have been observed near Sturgeon Lake during the winter months (Hanson et al., 2016). The lake also provides a valuable refuge for juvenile salmon to escape high flow periods in the Columbia River. By spending time in the lake avoiding these dangerous conditions, salmon have an opportunity to increase in size and heartiness, greatly increasing their survivability upon reaching the ocean (WMSWCD, 2020).

On the Columbia River, there are four salmonids of interest for this work: Coho, Chinook, Steelhead, and Chum. Typically, downstream migration of juvenile salmon toward saltwater occurs in the spring (Coho, Steelhead, Chum) or in the fall and spring (Steelhead), and most move to the ocean by June. For migratory birds, nesting and rearing in this area occurs during the winter and early spring, with most moving on by May. In the context of our study, this makes the winter months the most important time for which Sturgeon Lake's ecosystem needs to be maintained by the Dairy Creek Canal (Baker, 2008; ODFW, 2012; Josephson, 2021). In addition to Sturgeon Lake's environmental significance, it is also of great value to the local economy. Sauvie Island hosts approximately 800,000 people for recreational activities yearly (WMSWCD, 2020), supporting local businesses.

Models of future climate predict reduced seasonal snowpack in the Pacific Northwest region of the U.S., which may lead to a reduction in seasonal flooding in areas like Sauvie Island (Nolin and Daly, 2006). This, coupled with manmade levees in the area, would greatly restrict surface water flow into Sturgeon Lake and the floodplain of the island. One way to maintain flushing flows and a healthy hydrologic system in the area is through restoration canals such as the Dairy Creek Canal. These channels are designed to provide fish access to the lake and maintain the lake as a healthy ecosystem by providing flushing flow. As such, it is the aim of this study to evaluate how effective this canal is at reaching these goals. This study provides insight into how effective the restoration work has been and whether further work may be necessary.

2 Materials and methods

2.1 Field sampling

We conducted three years of field sampling from 2019 – 2022 on Sauvie Island and upstream along suspected water sources (Willamette River, Columbia River, and Multnomah Channel). Samples were collected twice yearly in the winter and summer (typically around June-July and December-January). In fall 2020, we introduced precipitation sampling. Precipitation samples were collected approximately every 30-60 days, representing cumulative precipitation from the last sampling date. Groundwater samples were collected from local wells intermittently as landowners allowed. Throughout the project, we collected a total of 77 surface water samples, 27 groundwater samples, and 42 precipitation samples. Due to limitations of the COVID-19 pandemic, we were unable to collect any samples during the summer of 2020 and were forced to collect a reduced number in the summer and winter of 2021. The dataset also includes published river water samples collected in the summer of 2018 (Saslaw and Bershaw, 2018).

Samples of Sturgeon Lake and small, connected water bodies were collected with assistance from the Oregon Department of Fish & Wildlife and the WMSWCD. River samples were taken upstream on the Willamette and Columbia Rivers to characterize the main sources of water in the lake. Surface samples also included the channel dredged at Dairy Creek and the Multnomah Channel, which runs along the western bank of Sauvie Island and receives water from Sturgeon Lake.

Precipitation samples were collected in 2 Palmex Rain Sampler RS-1s, which are designed to store collected precipitation for weeks, or even months, without losses through evaporation, which could alter the isotopic composition of samples. Rainwater enters an HDPE plastic bottle through a funnel and long intake tube.

Figure 3a (left). RS-1 precipitation sampler at the Portland, Oregon field site. The bottle in the foreground is the collection vessel, while the silver container in the background is the mount which contains the intake tube that prevents losses to evaporation.

Figure 3b (right). Disassembled RS-1 precipitation sampler showing the intake tube and bottle insert.

The RS-1 system does not require the use of oil to prevent evaporation as in other designs. Testing at the International Atomic Energy Agency showed that, over a 30-day period, isotopic composition experienced a change of +0.02‰ for $\delta^{18}O$ and +0.5‰ for $\delta^{2}H$. Over the course of 330 days the total change was +0.08‰ for $\delta^{18}O$ and +1.3‰ for $\delta^{2}H$. Overall, these minor changes in isotopic composition over long periods of time show that the system is highly effective in capturing and preserving the isotopic compositions of precipitation (Gröning et al., 2012).

Surface samples from 2018 to 2019 were collected using 15mL polystyrene centrifuge tubes, sterilized by gamma irradiation, sealed with Teflon tape, electrical tape, and stored in a refrigerator until analysis to minimize evaporation. Samples were sealed underwater to ensure minimal headspace. Post-2019 samples were collected using 50mL HDPE centrifuge tubes manufactured by Crystalgen, following the same sampling procedure. Precipitation samples were collected in the same Crystalgen tubes, though not sealed underwater due to the nature of the sampling system. Figure 1 shows the spatial distribution of water samples throughout the study area.

2.2 Stable isotope analysis

Analysis of 2018 samples was completed at Oregon State University using a Picarro model L2120-i water isotope analyzer. The analyzer vaporizes liquid from each sample and isotopes are measured in the gas phase using Wavelength-Scanned Cavity Ring-Down Spectroscopy (Gupta et al., 2009). Three known standards, including an ocean water sample approximating VSMOW, an Antarctic sample representing Standard Light Antarctic Precipitation, and a third Boulder, CO standard were interspersed with the collected samples to facilitate calibration and correct for drift. Total analytical precision is < 0.056‰ for $\delta^{18}O$ and < 0.313‰ for δ^2H.

2019 samples were analyzed using a Picarro L2130-i High Precision ^{18}O and ^2H Isotopic Water Analyzer using an A0211 High Precision Vaporizer and HTC PAL autosampler at the School of Ocean and Earth Science and Technology Isotope Biogeochemistry Laboratory, University of Hawai'i at Mānoa. The instrument was operated in high precision mode using ChemCorrect acquisition software that monitors for interference of the measured isotopologues of water by organic compounds. Samples containing visible particles were filtered (0.2 μm). Otherwise, samples were analyzed without pretreatment. All measurements were performed in the nitrogen carrier mode, using ultra-high-purity nitrogen. At least three laboratory reference waters were used to normalize the measured isotope ratios of samples to delta values relative to VSMOW and analyzed before and after every 10 samples. The isotopic composition of the laboratory reference waters were known through extensive calibration with reference materials supplied by the IAEA, Vienna, Austria. No samples of lake, river, or groundwater were identified as containing organic contamination by ChemCorrect software.

Post-2019 samples were analyzed at the Iowa State University Stable Isotope Lab using a Picarro L2130-i Isotopic Liquid Water Analyzer with CombiPAL autosampler. The analyzer operates using Wavelength Scanned Cavity Ringdown Spectroscopy (WS-CRDS). The precision of the WS-CRDS is ±0.10‰ for $\delta^{18}O$ and ±0.5‰ for δ^2H (Stable Isotope Lab, n.d.).

2.3 Modeling

To determine the residence time of the lake, we followed models described in Zanazzi et al. (2020). We assumed that Sturgeon Lake is at hydrologic steady state and that it is well-mixed. With this in mind, the residence time is given by

$$\tau = \frac{E}{I} \cdot \frac{V}{E_r}, \quad Eq.3$$

where τ is the residence time, *E/I* is the throughflow index (fraction of input lost to evaporation), *V* is the volume of the lake normalized to the lake surface by inputting the mean depth of the lake in mm, and E_r is the evaporation rate (mm day^{-1}) (Zanazzi et al., 2020). The throughflow index can be calculated as

$$\frac{E}{I} = \frac{\delta_L - \delta_I}{m \cdot (\delta^* - \delta_L)}, \quad Eq.4$$

where δ_L is the steady state delta value of the lake, δ_I is the delta values of the input water, δ^* is the limiting delta value of the lake (i.e., the delta value the water would approach if the lake were to evaporate uncontrolled without any additional input or other removal), and *m* is a constant (Zanazzi et al., 2022). Note that each of these parameters should be calculated using *either* $\delta^{18}O$ *or* $\delta^{2}H$ values—here, we calculate each parameter separately for each isotope, yielding two separate values for E/I. For our purposes, we assume that the groundwater input from the island to the lake has a similar isotopic composition to the rivers (Saslaw and Bershaw, 2018). Considering the lake's size and location, direct deposition of precipitation onto the lake is likely negligible.

2.4 Climate data

Climate data required for calculating modeling parameters were retrieved from three sources: 1) Weather Underground, a commercial weather service, Portland International Airport Station (humidity) (Weather Underground, n.d.); 2) the U.S. National Weather Service Vancouver Area Station (temperature) (NOAA, n.d.); and 3) the National Solar Radiation Database (solar radiation) (NSRDB, n.d.). For humidity and temperature, daily averages were used for each sampling date when available, and when unavailable, the average for the calendar month was used. For solar radiation, we retrieved data from two sites near Sturgeon Lake and averaged hourly radiation data for each sampling period from 3 different models: Direct Normal Irradiance, Diffuse Horizontal Irradiance, and Global Horizontal Irradiance.

2.5 Limitations

There is a significant disparity between the number of water samples collected in the winter and the number collected in the summer, in part due to the COVID-19 pandemic which limited our ability to collect summer samples in 2020 and 2021. However, in seasonally-focused limnology studies such as this, it has been shown that just one representative sample from a lake can provide an adequate first-order approximation for the throughflow index (Brooks et al., 2014). Because the residence time is based on elements of the throughflow index and lake volume (Equation 3), we can reasonably assume this holds for the residence time as well. The data from pre-restoration was also unfortunately too limited to perform the same modeling we used for post-restoration data and prevented us from drawing workable conclusions regarding how much change the ecosystem has experienced since the construction of the restoration canal.

3 Results

3.1 Isotopic delta values

Results are listed in Tables 1 and 2. For the Columbia and Willamette Rivers, there is some variation in $\delta^{18}O$ between the summer and winter, ranging from approximately -15.45 (summer) to -15.28 (winter) and -11.79 (summer) to -10.93 (winter), respectively. Variations in $\delta^{2}H$ range from approximately -116.91 (summer) to -113.04 (winter) and -84.38 (summer) to -75.27 (winter), respectively. The restoration canal itself also shows significant seasonal variation in both isotopes, ranging from -16.23 (summer) to -13.54 (winter) for $\delta^{18}O$ and -122.42 (summer) to -97.61 (winter) for $\delta^{2}H$. Note that winter values are more positive than summer, which is the opposite of what is observed in precipitation (this study and Rozanski et al., 1993), but consistent with other studies of surface water in the Pacific Northwest (Brooks et al., 2012). For Sturgeon Lake we see substantial variations in both $\delta^{18}O$ and $\delta^{2}H$, ranging from approximately -7.97 (summer) to -10.57 (winter) and -68.69 (summer) to -73.03 (winter), respectively. Lastly, for precipitation, we see small seasonal changes, ranging from -8.99

(summer) to -9.36 (winter) for $\delta^{18}O$ and -64.83 (summer) to -64.87 (winter) for $\delta^{2}H$. Unlike rivers and the canal, lake water and precipitation have higher values in the summer relative to the winter.

Table 1

*Summary of isotopic data from **summer** water samples.*

Water Body	Mean $\delta^{18}O$	SD	Mean $\delta^{2}H$	SD	Number of samples
Willamette River	-11.79	1.949	-84.38	17.238	8
Columbia River	-15.45	2.674	-116.92	21.364	7
Sturgeon Lake	-7.97	2.592	-68.69	14.872	11
D.C. Rest. Canal	-16.23	0.180	-122.42	1.945	4
Precipitation[a]	-8.99	2.289	-64.83	17.207	3

[a]Precipitation is the average of data from the Sauvie Island and Portland, OR sites.

Table 2

*Summary of isotopic data from **winter** water samples*

Water Body	Mean $\delta^{18}O$	SD	Mean $\delta^{2}H$	SD	Number of samples
Willamette River	-10.93	1.769	-75.273	15.016	12
Columbia River	-15.28	1.528	-113.04	13.350	12
Sturgeon Lake	-10.57	0.896	-73.03	7.660	11
D.C. Rest. Canal	-13.54	1.681	-97.61	16.120	3
Precipitation[a]	-9.36	1.906	-65.87	12.98	11

[a]Precipitation is the average of data from the Sauvie Island and Portland, OR sites.

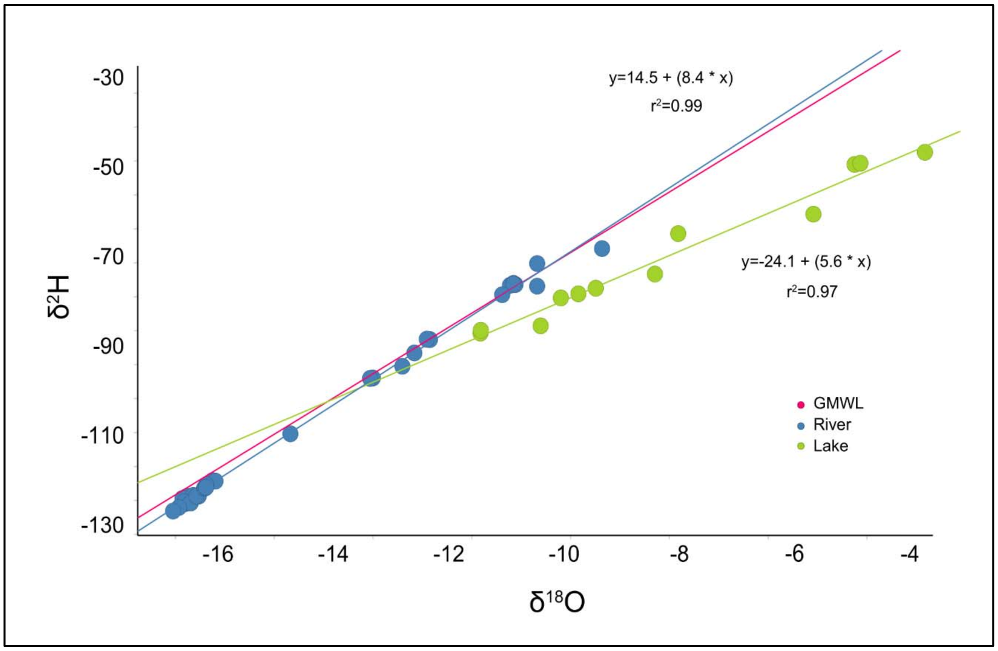

Figure 4a: Graph of summer water isotope values for each type of water body (river and lake). River values are presented in blue, lake values in green, and the GMWL in pink. The slope of Sturgeon Lake's meteoric water line (5.6) is significantly below that of the GMWL (8.00)

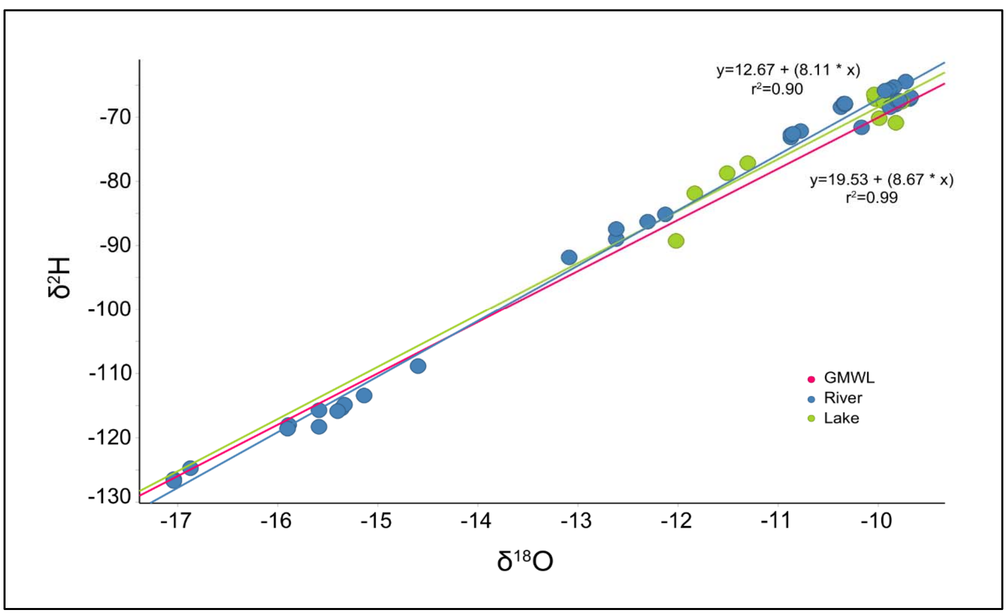

Figure 4b: Graph of winter water isotope values for each type of water body (river and lake). River values are presented in blue, lake values in green, and the GMWL in pink. The slope of both the river and the lake meteoric water lines are similar to that of the GMWL.

3.2 Modeling results

The following tables present the inputs and outputs of the models for throughflow index and residence time (Equations 3 and 4, respectively).

Table 3

Model input parameters

Parameter	Result
Average summer equilibrium fractionation factor (α^+) ($\delta^{18}O$)	1.009979
Average winter equilibrium fractionation factor (α^+) ($\delta^{18}O$)	1.011022
Average summer equilibrium fractionation factor (α^+) (δ^2H)	1.086893
Average winter equilibrium fractionation factor (α^+) (δ^2H)	1.101566
Average summer equilibrium isotopic separation (ε^+) ($\delta^{18}O$) (‰)	9.979
Average winter equilibrium isotopic separation (ε^+) ($\delta^{18}O$) (‰)	11.02
Average summer equilibrium isotopic separation (ε^+) (δ^2H) (‰)	86.89
Average winter equilibrium isotopic separation (ε^+) (δ^2H) (‰)	101.6
Average summer kinetic isotopic separation (ε_K) ($\delta^{18}O$) (‰)	6.23
Average winter kinetic isotopic separation (ε_K) ($\delta^{18}O$) (‰)	3.51
Average summer kinetic isotopic separation (ε_K) (δ^2H) (‰)	5.49
Average winter kinetic isotopic separation (ε_K) (δ^2H) (‰)	3.09
Average summer *m* (Lake) ($\delta^{18}O$)	1.172
Average winter *m* (Lake) ($\delta^{18}O$)	4.133
Average summer *m* (Lake) (δ^2H)	1.022
Average winter *m* (Lake) (δ^2H)	3.725
Average summer *m* (Rivers) ($\delta^{18}O$)	1.266
Average winter *m* (Rivers) ($\delta^{18}O$)	3.580
Average summer *m* (Rivers) (δ^2H)	1.110
Average winter *m* (Rivers) (δ^2H)	3.212
Summer limiting delta value of the lake (δ*) ($\delta^{18}O$) (‰)	10.65
Winter limiting delta value of the lake (δ*) ($\delta^{18}O$) (‰)	-3.385
Summer limiting delta value of the lake (δ*) (δ^2H) (‰)	13.08

Winter limiting delta value of the lake (δ*) (δ^2H) (‰)	-42.59
Average summer surface radiation ($MJ*m^{-2}*day^{-1}$)	29.401
Average winter surface radiation ($MJ*m^{-2}*day^{-1}$)	20.502
Average summer extraterrestrial radiation ($MJ*m^{-2}*day^{-1}$)	41.152
Average winter extraterrestrial radiation ($MJ*m^{-2}*day^{-1}$)	18.370
Summer lake evaporation rate (E_r) (mm/day)	7.44
Winter lake evaporation rate (E_r) (mm/day)	1.49
Winter approximate lake depth (mm)	1219.2[a]
Summer approximate lake depth (mm)	457.2[a]

Note. The table is organized as follows: "Parameter name," (parameter symbol) (isotope used for calculation) (units). [a]HDR Engineering, Inc., 2013.

Table 4

Model outputs

Parameter	Result
Summer $\delta^{18}O$ throughflow index (E/I)	0.2835
Summer δ^2H throughflow index (E/I)	0.4470
Average summer throughflow index (E/I)	0.3653
Winter $\delta^{18}O$ throughflow index (E/I)	0.0610
Winter δ^2H throughflow index (E/I)	0.1297
Average winter throughflow index (E/I)	0.0953
Sturgeon lake average residence time (τ) (days)	43.2

4 Discussion

Using the throughflow index results, we can begin to interpret the overall biological conditions in Sturgeon Lake between seasons. The average of summer months in 2020 and 2021 shows a throughflow index of 0.3653, indicating approximately 36.53% of inflow is lost to evaporation. We expect that this is associated with a significant degradation in ecosystem quality during the summer as poor biological conditions in this region are associated with throughflow indices larger than 0.1 (based on planktonic models) (Brooks et al., 2014). In contrast, our estimated throughflow index in the winter months is only 0.0953, indicating approximately 9.53% of inflow lost to evaporation. Though it is close to the threshold for poor biological conditions (placing it in the “fair” category according to the model in Brooks et al. (2014)), this is vastly improved compared to summer months, and indicates that the ecosystem is healthier during winter. With such a low E/I value, Sturgeon Lake is likely receiving enough flushing flow in the winter to maintain the ecological quality of the lake.

The mean residence time for lake water during the study period was approximately 43.2 days, with a summer residence time of 22.5 days and a winter residence time of 77.8 days. While quantitative correlations between residence times and ecosystem health are not well-established, evidence that shorter residence times are linked with poor lake health (Brooks et al., 2014) supports the observation that the Sturgeon Lake ecosystem is degrading in the summer based on the throughflow index. While it is unclear what drives this connection between short residence times and poor lake health, there is a clear jump in the amount of inflow lost to evaporation between the summer and winter. It is possible that increasing the throughflow index (i.e., increasing the amount of input lost to evaporation) would reduce the residence time by increasing flux through the lake. Thus, the link between short residence times and poor ecosystem quality may be an artifact of the throughflow index. Since we know that higher throughflow index indicates poor ecosystem quality, and higher throughflow index leads to shorter residence times, it appears that shorter residence times are also linked to poor ecosystem quality. The size of the lake is also multiple times larger in winter compared to summer, resulting in larger residence times as the two are directly correlated (Eq. 3).

As described in Section 1.2.4, Sturgeon Lake's primary ecosystem function for native salmonids and migratory bird species takes place during the winter, with some use in the fall and spring (Baker, 2008; ODFW, 2012; Josephson, 2021). In addition, the lake and surrounding area's recreational appeal is primarily during hunting season in the late fall/early winter. Our results suggest that the canal plays a role in maintaining the ecosystem in and around Sturgeon Lake by allowing throughflow and decreasing stagnation during the winter.

5 Conclusions and future work

It is clear from the presented results for the throughflow index (0.3653 in the summer, 0.0953 in the winter) and the residence time (43.2 days) that Sturgeon Lake exhibits good biological condition during the winter but may suffer from stagnation and ecosystem degradation during the summer. Despite this, we conclude that the Dairy Creek canal is effective in achieving its goal of maintaining habitat for juvenile salmon and migratory birds, as these species use the lake almost exclusively in the winter. These results provide valuable insight into the dynamics of the lake's ecosystem, and will hopefully inform future engineering and restoration efforts, either in improving the Sturgeon Lake ecosystem in the summer or at other, similar lakes in the region.

5.1 Recommendations for future work

We recommend several focuses for future work in this area. As mentioned above, one of the critical issues in Sturgeon Lake is a dangerous buildup of coliform bacteria (Klingeman, 1987). At the time of writing, the cause of this buildup remains unknown. An ecological study into the sources of this bacteria may benefit the understanding and management of the Sturgeon Lake ecosystem.

Relating to the activities performed in this study, we acknowledge several limitations that we attempted to overcome in the preparation of this article: due to the COVID-19 pandemic, we were unable to obtain an ideal number of summer water samples, both for surface water and for precipitation. As such, we recommend that future isotopic studies obtain a higher temporal resolution of samples to work with, including fall and spring sampling to fill gaps in the presented dataset. Having data from all four seasons in particular will help to better investigate potential effects on specific salmonid species' various spawning months. Alongside this, a higher spatial resolution would be helpful. There are several large ponds and lakes around Sturgeon Lake that are separated by manmade barriers and were thus excluded from our sampling campaign but have the potential to exchange water through seepage or flooding—obtaining isotopic samples from these may yield new insights into the hydrosphere of Sauvie Island.

Due to challenges around working with private landowners and the distribution of existing groundwater wells, we were unable to obtain sufficient spatial coverage of groundwater samples to effectively incorporate them into our discussion. Future work could potentially find a way to improve coverage of groundwater samples and use them to estimate the influences of groundwater input to the lake. As we described previously, it is unlikely that a different isotope signature from groundwater significantly influences the lake—poorly consolidated gravels allow meteoric waters to infiltrate and mix in the floodplain deposit, and no deep groundwater sources are identified nearby (Evarts et al., 2016).

Lastly, measurements of discharge volume and flow direction in Dairy Creek and Gilbert River would likely yield valuable insights as well, allowing future researchers to better understand the throughflow dynamics of the lake and attempt volume-weighted calculations of E/I and residence time.

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Open Research

The solar radiation data used for calculating parameters in Table 3 are available at the National Solar Radiation Database via https://nsrdb.nrel.gov/data-sets/us-data.

The humidity data used for calculating parameters in Table 3 are available at Weather Underground (using the Portland International Airport station) via https://www.wunderground.com/history.

The air temperature data used for calculating parameters in Table 3 are available at the U.S. National Weather Service (using the Vancouver 4NNE station or Vancouver Area, depending on version) via https://www.weather.gov/wrh/climate?wfo=pqr.

The isotope ratio data for samples we collected used throughout will be published with PDXScholar, Portland State University's institutional repository available via https://pdxscholar.library.pdx.edu/.

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