Exploring the Potential of Remote Sensing-based River Temperature Tool for Improving Columbia River Reservoir Management Towards Fish Abundance Outcomes

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Key Points:

- A data-driven and remote-sensing-based water temperature tool has value in informing reservoir management for fish abundance in the Columbia River.
- River temperature during the fall fish migration period in the Hanford Reach of Columbia River basin has experienced an increasing trend over the last decade.
- Meeting discharge requirements for fish passage needs to be supplemented with temperature requirements to ensure the survival of downstream fish.
- The remote sensing tool can inform these temperature requirements based on a 40 year analysis of data

Abstract

The thermal condition of riverine ecosystems significantly influences fish survival and migration. Understanding the spatial relationship between water temperature and fish abundance requires a comprehensive spatiotemporal overview of river temperature. In this study, we used multi-decadal spatiotemporal river temperature estimates from the Thermal History of Regulated Rivers (THORR) tool to explore the relationship between water temperature, fish abundance, and migration patterns. We demonstrated the potential of such a tool and the corresponding analyses to inform and improve reservoir management for fish abundance. Our assessment, based on the mass balance concept, considered the influx and efflux of migratory fish during the fall season in the Hanford Reach along the Columbia River to determine fish retention. We found that the proportion of fish leaving the reach increases with rising water temperatures. Although fish appear to travel faster at higher temperatures according to THORR-based analyses, discharge-focused dam operations upstream did not result in downstream cooling, thus failing to improve thermal conditions for fish in the downstream reach. A long-term multi-decadal trend showed a significant increase in fall water temperatures beyond stressful levels over the past decade. These findings underscore the critical need for balanced dam operations that consider both discharge and temperature requirements to ensure optimal conditions for fish survival and migration. The insights provided by the THORR tool not only enhance our understanding of riverine thermal dynamics but also offer a valuable resource for developing sustainable water management practices in regulated rivers where fish passage is critical. By leveraging THORR's capabilities, we can better plan ways to protect aquatic ecosystems, support biodiversity, and promote the resilience of fish populations amidst climate change impacts.

Keywords: River temperature, remote sensing, Columbia River, reservoirs and fish

1 Introduction

Water temperature is an important water quality parameter that influences the survival of fish and other aquatic organisms and serves as an environmental cue for processes such as migration and reproduction (Chen et al., 2023). For example, the thermal conditions of the ocean and rivers affect the migration timing and fluctuations in the abundance of anadromous fish such as salmonids (Keefer et al., 2018; U.S. Environmental Protection Agency. Region X, 2003). Some of the major factors affecting the thermal conditions of rivers include adjacent topography, atmospheric conditions, streambed, and stream discharge (Caissie, 2006). Changes in these factors can occur naturally but the rate of influence is accelerated or intensified by human-induced drivers such as land-use change through urbanization, agriculture, and modifications to rivers through diversions and dams (Ficklin et al., 2023; Heggenes et al., 2021).

The presence of dams affects water temperature in several ways such as physically fragmenting rivers, resulting in thermal discontinuities and barriers to fish passage in the river network (Chen et al., 2023; Keefer et al., 2018). Deep reservoirs can also induce thermal stratification, leading to downstream cooling during warmer seasons and occasional warming during colder seasons (Ahmad et al., 2021; Bonnema et al., 2020; Olden & Naiman, 2010). The Columbia River Basin (CRB) is a typical example of a heavily regulated river network with over 250 dams. The reservoirs within the CRB serve as a vital water source for irrigation and contribute significantly to the hydropower generation in the Pacific Northwest, accounting for more than 40% of the hydroelectric power in the United States (U.S.) (Lillis, 2014). However, the unnatural alteration of river conditions in the CRB by dams disrupts the thermal regime of the river network, which can adversely affect the survival, reproduction, migration timing, and distribution of fish within the riverine ecosystem (Chen et al., 2023; Li et al., 2021; Wilson et al., 2023).

Efforts to address the issue of a physical barrier include the removal of existing dams such as the Elwha and Glines Canyon dams. Such removals have resulted in an impactful restoration of the aquatic ecosystem and a significant return of salmon and other riverine species (Anne Shaffer et al., 2017; Brenkman et al., 2019). Although drastic and effective, dam removal is not always feasible when the benefits from dams are weighed against the cost of dam demolition. The construction of fish ladders at dam sites, such as the Bonneville dam along the Columbia River and the Ice Harbor dam along the Snake River in the CRB, is an example of another measure that facilitates the safe passage of salmonids to their spawning sites (Keefer et al., 1996; Reischel & Bjornn, 2003). Addressing the physical barrier is just one facet of the solution. However, addressing the environmental conditions of the river such as water temperature can also play an important role in restoring or maintaining a favorable habitat for fish in the regulated river system of the CRB.

Among the environmental parameters that affect fish in regulated rivers, flow, and temperature are easily assessable and manageable (Paragamian & Wakkinen, 2002). However, in managing the environmental criteria in regulated rivers, flow receives more attention than temperature, partly due to the paucity of water temperature measurements and the lack of long-term data to facilitate studies across qualitatively different regulated rivers and their thermal impacts (Olden & Naiman, 2010). Efforts to maintain ecologically favorable river temperatures for fish in regulated river networks include selective downstream discharge and dam operation plans that prioritize releases focusing on both discharge and temperature requirements for fish (Kim & Choi, 2021; Olden & Naiman, 2010), for example, the Cougar Dam on the South Fork McKenzie River in Oregon, U.S. (Murphy et al., 2021), and Shasta Dam on the Sacramento River in California, U.S. (Hanna et al., 1999; Zarri et al., 2019). Throughout the lifecycle of fish species such as salmon, riverine thermal conditions, among other environmental parameters, can have immediate consequences (Brett, 1952) as well as long-term consequences where the thermal conditions at juvenile stages can have dynamic effects in their adult stage (Cordoleani et al., 2021).

Therefore, the effectiveness of dam operations to meet the water temperature requirements for fish in the river network requires extensive spatiotemporal studies. However, such extensive studies on regulated river water temperature are limited by the sparse nature of in-situ water temperature data (Olden & Naiman, 2010). Spatially, the in-situ temperature data represent point measurements that may not be representative of long reaches of rivers that do not have installed water temperature gauges. In the case of rivers, such as the Columbia River, that cross international boundaries, in-situ temperature datasets may not be readily accessible or shared across borders. This limits the spatial overview of river temperature throughout the river network. Moreover, some streams may be physically inaccessible, making it difficult to obtain in-situ water temperature datasets for such locations.

Advances in river temperature monitoring have significantly benefited from the use of thermal infrared (TIR) sensors, which offer extensive spatial coverage (Handcock et al., 2012). TIR sensors mounted on aircraft provide high-resolution observations and can avoid cloud obstruction. However, the cost of multiple deployments for extensive temporal studies can be a limitation (Torgersen et al., 2001). While airborne TIR observations cover wider areas than in-situ measurements, they are typically restricted to local extents, such as river segments. Satellite-based TIR remote sensing, on the other hand, provides broader spatial coverage and long-term historical data, making it suitable for large-scale, basin-wide, and long-term studies. Despite these advantages, satellite-based TIR can be hindered by cloud cover and lower spatial resolution, which poses challenges for assessing water temperatures in narrow rivers (Handcock et al., 2006).

To extend the use of satellite-based TIR remote sensing that now has more than 40 years of observations, Darkwah et al. (2024) developed the Thermal History of Regulated Rivers (THORR) tool that generates all-weather, continuous spatial and temporal river water temperature data from Landsat TIR for both wide and narrow rivers. THORR extends the historical record of water temperature back to 1982 (i.e., since the inception of the Landsat 4 mission). Supplementing in-situ water temperature with THORR water temperature estimates offers significant potential for reservoir and basin management, aiding in the protection of riverine ecosystems. While river regulation provides benefits such as irrigation, hydropower generation, and flood control, dam operations significantly impact water temperature both upstream and downstream (Chen et al., 2023). THORR enables the exploration of these impacts over longitudinal extents, a task previously challenging with only in-situ point-based measurements.

THORR can generate long-term multi-decadal historical patterns of river temperature variations, potentially informing the consequences of past dam operations and management decisions. Such information can support the adoption of best river and reservoir management practices and the modification of detrimental ones affecting riverine ecosystems. Given the important role of water temperature for aquatic organisms, a comprehensive spatiotemporal analysis is essential for understanding biological processes like fish migration and its abundance. THORR's ability to fill the gap in multi-decadal, basin-wide, and continuous river temperature records allows, for the first time, the assessment of spatiotemporal dynamics in fish populations relative to riverine water temperature. Additionally, THORR's design ensures it is accessible and scalable, even in areas lacking existing in-situ temperature measurements. THORR, however, is not without limitations. Because THORR’s water temperature estimates are aggregated at 10-km reaches, it may not be suitable for studying processes that occur at scales finer than 10 km. THORR is also frequency-limited due to satellite overpasses that occur at weekly intervals. Finally, we acknowledge that THORR’s temperature estimates are not equivalent to depth-averaged water temperature.

Our study aims to explore the potential of the data-driven remote sensing tool called THORR that can track river temperature to inform reservoir management towards improved fish abundance outcomes. Specifically, we ask, *'Given the water temperature tracking breakthroughs enabled by a data-driven and remote sensing tool such as THORR, what is the potential for improving reservoir management to realize better abundance outcomes for fish for the Columbia River Basin?'* We ask this question by mapping comprehensive fish count data on the river temperature space defined by THORR data. Through this mapping, we explore what potential insights THORR can reveal that were not possible earlier and may have potential value for informing reservoir management strategies moving forward. Our mapping of fish count data on the THORR-based temperature space is driven by the following three specific questions: 1) How strongly are shifts in fish abundance connected to temperature changes? 2) What is the historical correlation between water temperature trends and migration timing and speed of anadromous fish? 3) How are these trends in temperature and fish dynamics related to dam operations?

We leverage extensive and continuous spatiotemporal temperature estimates of THORR derived from satellite remote sensing and data-driven methods. This approach provides a long-term history of water temperature with broad spatial coverage that helps us investigate the complex relationships between dam operations, water temperature, and salmon migration patterns for the CRB. The overarching goal of our study is to demonstrate the potential of a tool like THORR for real-world decision-making. Here, we use THORR’s long-term historical water temperature to understand how river and reservoir management influence fish abundance.

In this article, we described the study area, the data used, and our general approach in the Methods section. The outcomes of our assessments are presented in the Results followed by a detailed Discussion section that explains our results and links the outcomes of this study to possible recommendations for effective dam operation.

2 Methods

2.1 Study Area

The Columbia River Basin (CRB), located in the Pacific Northwest Region, spans seven states in the U.S. and British Columbia (BC), Canada. Its major river, the Columbia River, is approximately 2000 km long and originates from the Kootenay mountain range in BC. The Columbia River flows northwest from its headwaters and meanders southward into the U.S. State of Washington before flowing into the Pacific Ocean (Keefer et al., 2018) (Figure 1). The Columbia River and its tributaries serve as a rich habitat for Pacific salmon species and trout. Adult salmon migrate from the Pacific into the basin’s rivers to spawn and juvenile salmon, after development, out-migrate from the rivers into the ocean (Keefer et al., 2004). Economically, the CRB plays a pivotal role, providing irrigation for agriculture, hydroelectric power generation, navigation channels for shipping, and recreational activities (Stanford et al., 2023).

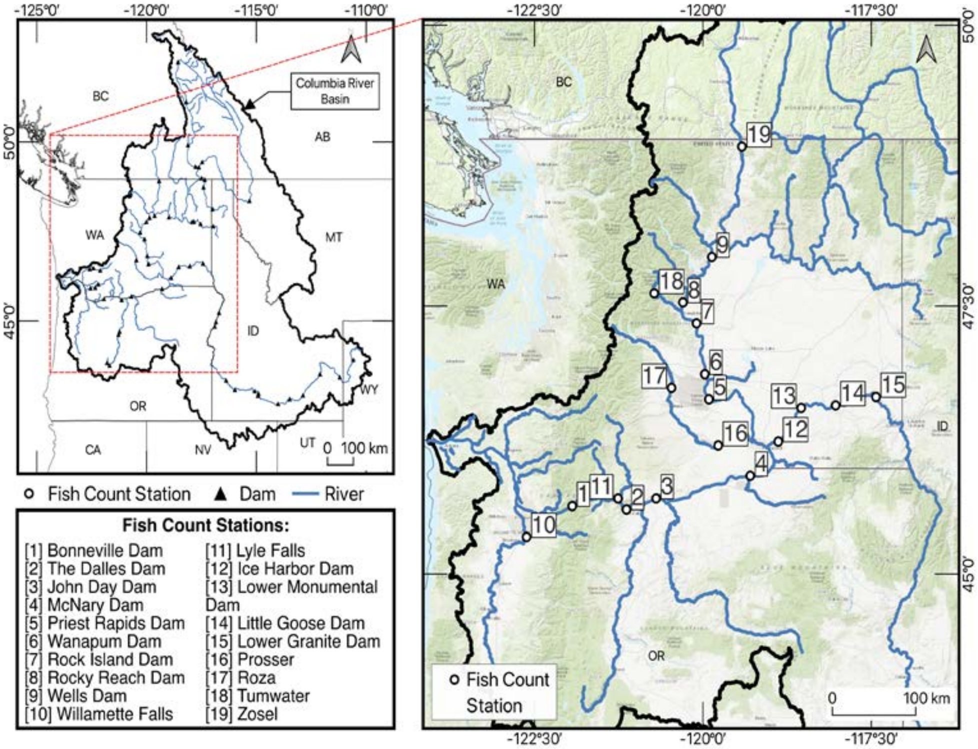

Figure 1. A map of the Columbia River Basin showing the dams along the Columbia River and its major tributaries, featuring fish passages where migrating fish are counted.

The Columbia River can be divided into three major segments: the Lower Columbia, Middle Columbia, and Upper Columbia. The Lower Columbia starts from the Pacific Ocean to the Bonneville Dam, approximately river kilometer (Rkm) 230. Here, we do not focus on the Lower Columbia given the complex nature of thermal and hydraulic interaction at the tidal interface with the ocean. We consider the section of the Columbia River upstream of the Bonneville Dam as a pristine riverine environment. However, we limit our study to Middle Columbia which extends from the Bonneville Dam upstream to the Grand Coulee Dam (Rkm 960). This is because there is no fish passage at the Grand Coulee Dam to allow migratory fish beyond the dam. Therefore, Middle Columbia encompasses the scope of our study: the intersection between river temperature and fish. A key section of the Middle Columbia is the Hanford Reach between McNary Dam (Rkm 470) and Priest Rapids Dam (Rkm 640), the longest free-flowing reach along the Columbia River. The Yakima and Snake rivers join the Columbia River at the Hanford reach (Figure 2). The reach serves as a major migration corridor and spawning habitat for fall Chinook salmon in the CRB (Dauble & Watson, 1990). Flow through the Hanford reach is mainly controlled by upstream discharge from the Priest Rapids dam, with a mean average discharge of 3,500 m^3/s (Dauble & Geist, 2000). We consider the entire section of the Columbia River from McNary Dam up to Priest Rapids, including the Hanford reach as a single control unit for our analyses. Although the Hanford Reach is approximately 70 km downstream of the Priest Rapids Dam, we will refer to the entire section of the Columbia from McNary Dam to Priest Rapids Dam as the Hanford Reach hereafter.

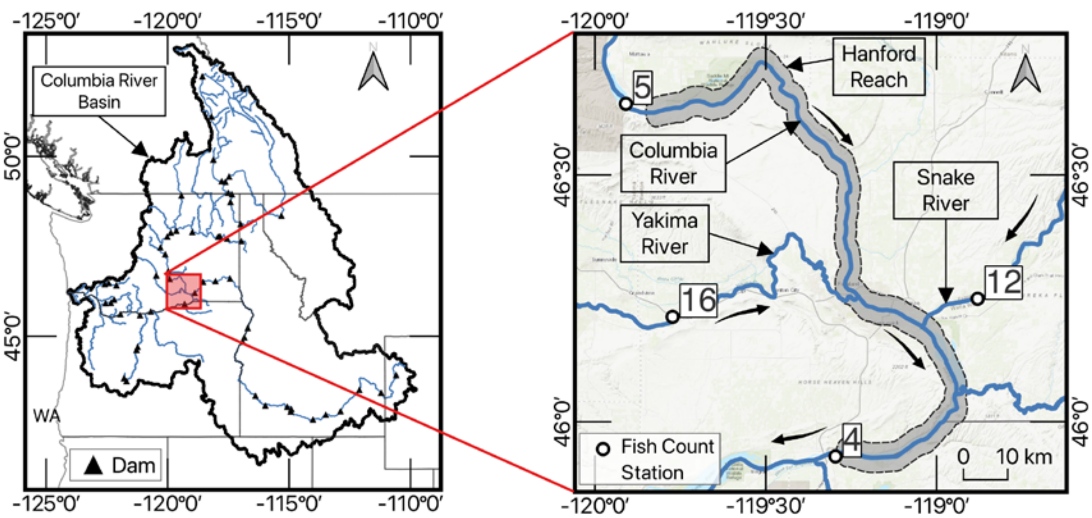

Figure 2. The Hanford Reach along the Columbia River. The reach is bounded downstream by the McNary Dam (Label 4) and upstream by the Priest Rapids Dam (label 5). The Snake and Yakima rivers join the Columbia River at this Reach with fish count stations at Ice Harbor Dam (label 12) and Prosser (label 16) respectively. Tapered arrows indicate the direction of flow within the river network.

2.2 Data

2.2.1 Spatiotemporal Water Temperature Data

A continuous spatiotemporal representation of water temperature in the Columbia River basin is necessary to understand how fish migration relates to riverine temperature. Along the Columbia River and its tributaries, there are in-situ water temperature records that are accessible through the U.S. Geological Survey (USGS)[1], the U.S. Bureau of Reclamation (USBR)[2], or the Columbia Basin Research Data Access in Real Time (CBR-DART)[3] which collates additional water temperature data from the U.S. Army Corps of Engineers (USACE), NWD and the Grant County Public Utility District. However, the mode of in-situ water temperature measurement, usually by a temperature probe at a single location, limits the water temperature observations to the observation point. For a spatially representative outlook on water temperature within the CRB, we obtained a continuous spatiotemporal water temperature using THORR (Darkwah et al., 2024). As mentioned earlier, THORR is a tool that utilizes data-driven techniques and satellite TIR data to generate river temperature. This data is generated for every 10 km reach length along the basin’s river network (Figure 3). The THORR temperature data dates back from 1982 onwards, providing a long-term overview of the trends and patterns within the Columbia River basin. In this study, we utilized water temperature data from August 1985 through December 2023 (39 years), aggregated on a weekly basis. Where necessary, we limit the extent of the water temperature used in analyses to align with the available fish count data (see Section 2.2.2).

[1] USGS data access: https://dashboard.waterdata.usgs.gov/
[2] USBR data access: https://www.usbr.gov/pn/hydromet/
[3] CBR-DART data access: https://www.cbr.washington.edu/dart/query/river_graph_text

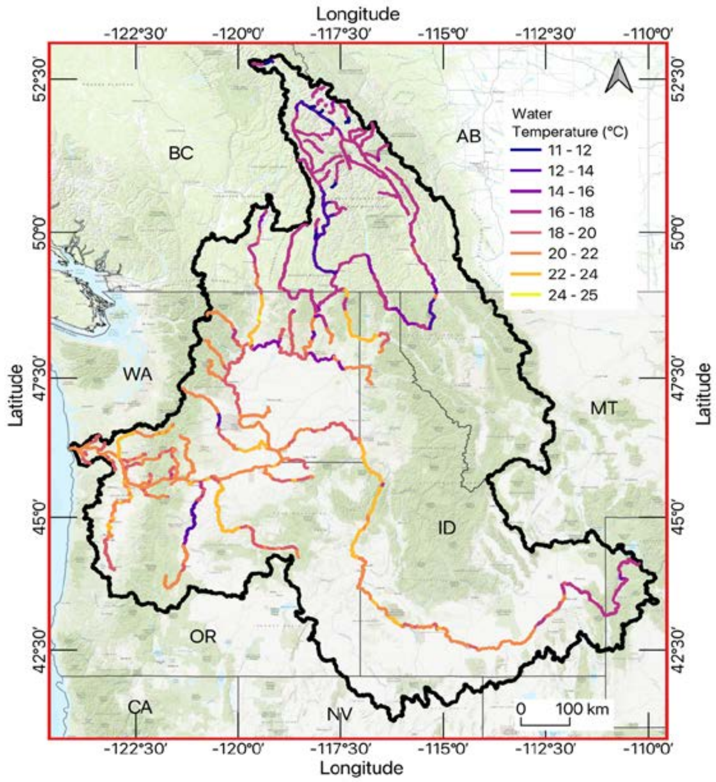

Figure 3. An example of THORR water temperature estimates for the Columbia River basin, showing the average estimated water temperature in August 2023. The water temperature is provided for 10-km reach intervals along the river network and is accessible at https://depts.washington.edu/saswe/thorr.

2.2.2 Fish Count Data

The Columbia River basin serves as a habitat for several aquatic species including steelhead, trout, and salmonids. There are infrastructures such as fish ladders located at most dams to allow the free passage of migratory fish in and out of the basin's waterways. At these locations, the passing fish are counted visually or through Passive Integrated Transponder (PIT) tags. The visual counts in the Columbia River basin take place at fish count stations located at USACE dams that have fish ladders (Figure 1). The fish counters then submit daily fish counts from video recordings at the fish count stations. The fish counts can be categorized into different runs depending on the time of the year (Figure 4). The PIT tags are radio-frequency identification (RFID) devices inserted into fish, usually at the juvenile stage (McCutcheon et al., 1994). The tags can be detected and decoded as tagged fish pass by detectors at the monitory locations. The PIT tags bear unique identities and attributes such as tag site and release date that make it possible to track the movement of individual fish within, out of, or into the basin's river network. While visual counts represent the entire number of fish crossing the passage, the PIT tag information is limited to tagged fish, hence a difference in counts (Figure 5).

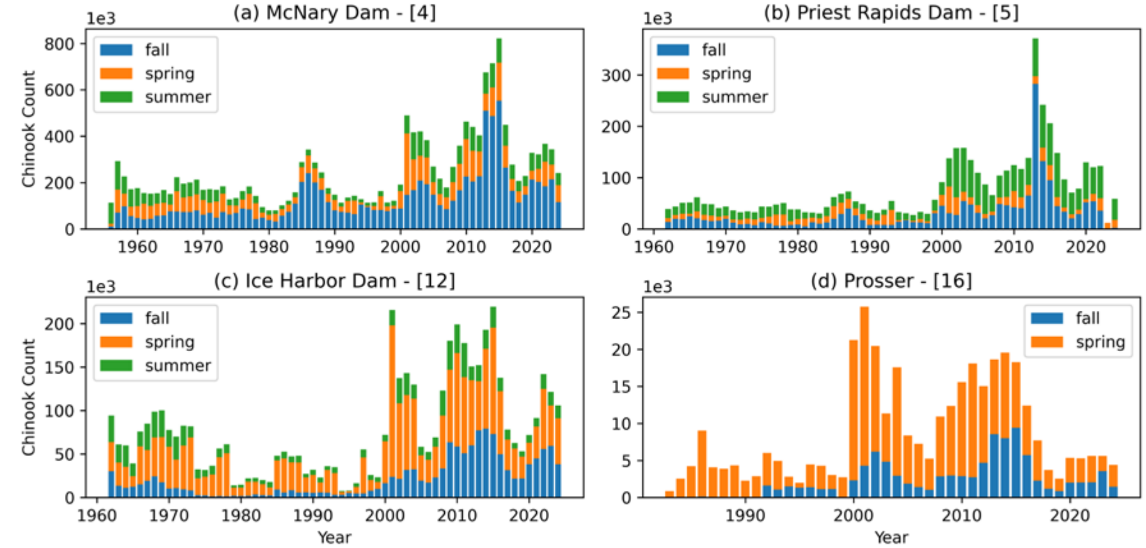

Figure 4. Yearly fish counts of adult Chinook salmon migrating upstream at a) McNary Dam, b) Priest Rapids Dam, c) Ice Harbor Dam, and d) Prosser Dam. The number of fish observed at these locations is grouped into migration seasons where there is available data.

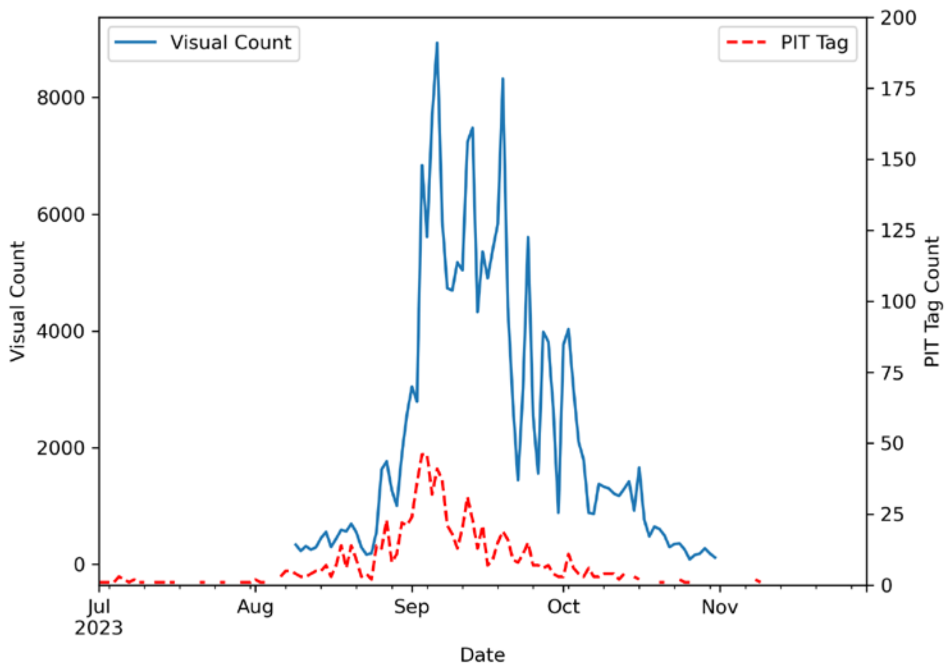

Figure 5. Visual and PIT tag fish counts of adult Chinook salmon species migrating upstream across the McNary Dam (Columbia River - Rkm 470) in the Fall run of 2023.

The visual fish count and PIT tag data can be grouped based on the fish species and their development stage (adult or juvenile). With a focus on salmonid species, the data can be further filtered by the run (the season when adult salmon migrate into the basin), and the rear type (hatchery or wild). Although the data comprises Chinook, coho, pink, chum, and sockeye salmon species in the CRB, we focus on the Chinook species, which has the highest abundance in the CRB, for the analyses in this study.

2.2.3 Stream Discharge Data

In addition to the in-situ water temperature data from the USGS, USBR, and CBR-DART, most of the gauge stations also record stream discharge. However, we focused on using daily stream discharge data from the CBR-DART since the data from these locations are directly located at the fish count stations. We aggregated the daily stream discharge into weekly averages at each location in our analyses. The discharge records used span from August 1985 through December 2024, in alignment with the available fish count data.

2.3 Mass Balance Approach to Fish Abundance

In order to explore the potential of THORR for understanding how river and reservoir management can be improved for better fish abundance outcomes, we took a mass balance approach for fish count data. The fate of anadromous fish such as salmon, as they arrive at a given river reach, is to either travel across the reach to a final destination (natal site) or remain within the reach to spawn, and eventually die if not harvested. Given a defined entry and exit location (with fish counts) in a river reach, we liken the movement of fish to the concept of mass balance where the abundance of fish, *F*, within the river reach, is considered a control volume (Figure 6).

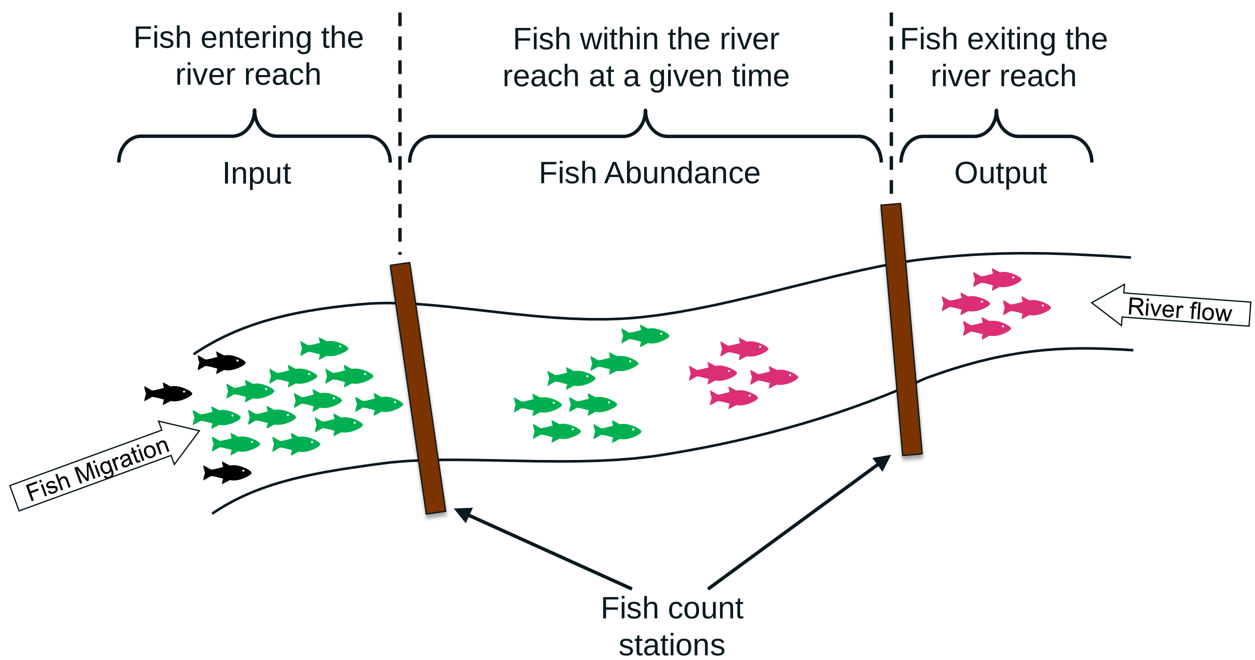

Figure 6. A schematic of the mass balance approach to fish abundance. The illustration shows adult fish migrating upstream into a given reach bound by fish count stations.

Comparing the dynamics of fish abundance to the water temperature dynamics can elicit an understanding of the migration and retention patterns of fish. The change in fish abundance within a given reach is therefore given by:

$$\Delta F = I - O \quad (1)$$

where ΔF is the change in fish abundance, I is the number of fish entering the river reach, and O is the total number of fish leaving the reach. Based on the concept of mass balance, positive ΔF indicates a high retention of fish within the given reach while negative ΔF means more fish are leaving the reach than entering, hence a declining abundance in the reach. We understand that such an approach may not necessarily be grounded in biology, but we believe it is reasonable to understand the potential of THORR for informing reservoir management based on river temperature data, which is the goal of our study.

Applying Equation (1) to the adult Chinook salmon return in the Hanford reach (Figure 2), the input will be given by the number of Chinook salmon observed at the McNary Dam and the output will be the sum of Chinook salmon observed at the upstream locations, that are Priest Rapids Dam, Ice Harbor Dam and Prosser (Figure 7). Our mass balance approach to fish abundance assumes simultaneous observations at both the input and output locations. However, the initial wave of fish observed at the output stations occurs later than at the input stations due to travel time through the reach. To account for this, we applied a time shift adjustment to the observations at upstream fish count stations. These time shifts were approximated based on the reported start dates of the fall run schedules at each fish count station, as published on the CBR-DART webpage (https://www.cbr.washington.edu/dart/metadata/adult) (Table 1).

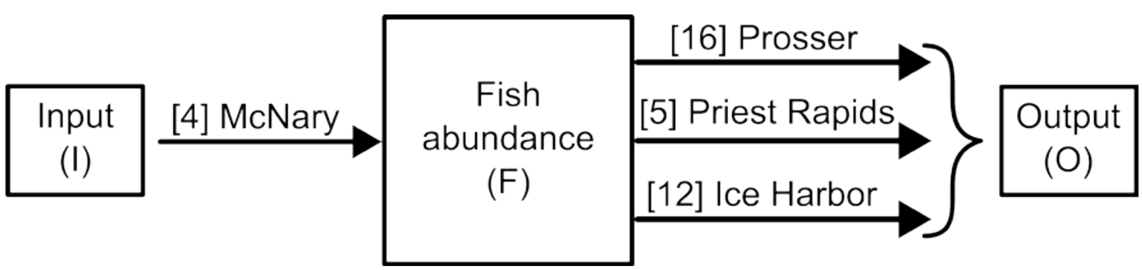

Figure 7. Graphical representation of the mass balance concept to adult Chinook salmon abundance at the Hanford Reach. The fish enter the reach through the McNary Dam which constitutes the input (I) and exit the reach at the Priest Rapids Dam, Ice Harbor Dam, and Prosser which constitutes the output (O).

Table 1. Time shift adjustments to observations made at fish count stations at the Hanford Reach.

Fish Count Station	Station No.	Fall Run Start Date	Time shift (days)
McNary	4	9 August	0
Priest Rapids	5	14 August	-5
Ice Harbor	12	12 August	-3
Prosser	16	16 August	-7

The time-varying nature of the fish count entering a particular reach (as seen in Figure 4) may be due to multiple factors such as the ocean environment prior to the adult fish migration or the river environment at the juvenile stages of the return adult fish. To limit our analyses of fish abundance in the reach to the conditions within the reach, we also define the fish retention ratio as a normalized metric given:

$$R = \frac{\Delta F}{I} \tag{2}$$

where the fish retention ratio, *R*, represents the fraction of fish entering the reach that remained in the reach. A maximum *R* value of 1 implies that all the fish that entered the reach did not leave within a given period whereas an *R* of 0 implies that the total amount of fish that entered the reach was balanced out by the same number of fish leaving the reach. Given a non-negative *I* value, a negative *R* means that pre-existing fish within the reach traveled upstream in the given timeframe. The fish retention ratio can signify the rate of travel through the reach during migration. We should note that such an approach defined by Equation 1 does not account for other factors that can impact the retention, such as predation, fishing, water toxicity (e.g. harmful algal bloom).

2.4 Relationship between water temperature and fish abundance

We integrated the mass balance concept of fish abundance (Section 2.2) with spatial water temperature data from THORR to evaluate the long-term relationship between fish abundance and temperature. For a specific river section, like the Columbia River from McNary Dam (Rkm 470) to Priest Rapids Dam (Rkm 640), multiple water temperature estimates were available, as the THORR dataset is divided into 10-km reach segments. We averaged all the available temperature estimates from THORR within the reach for the relevant time frame. We derived the fish abundance by summing the number of fish observed at each fish count station. For instance, for a weekly assessment of fish abundance and water temperature, we calculated the average of all estimated temperatures across sub-segments on a weekly basis to align with the weekly sum of fish observed within the reach. This method of aggregation can also be applied to assessments that require monthly or seasonal averages.

3 Results

3.1 Trends in Water Temperature, Fish Abundance, and Discharge

Several factors affect local fish populations, including water temperature and flow (Paragamian & Wakkinen, 2002). In the Hanford Reach (Figure 2), the average water temperature is around 20.8 °C as informed by THORR since in-situ probes cannot provide reach-averaged estimates (Figure 8a). At the onset of the adult Chinook salmon migration season, temperatures can range from 19.4 °C to 21.8 °C. The temperature stays above 20 °C for the first 30 days of the run, then gradually drops below 15 °C by the end of the fall migration season (Figure 8a). Flow within the Hanford Reach, primarily controlled by the upstream discharge at Priest Rapids Dam, is highest at the start of the fall run. The average discharge ranges from 200 to 400 $x10^6$ m^3/day and decreases gradually until about 40 days into the migration season. After this period, the discharge stabilizes at a lower, more uniform rate through the end of the season (Figure 8b). Adult Chinook salmon entering the Hanford Reach during the fall migration season start to trickle in until the 20th day, then their numbers ramp up to a peak around day 40. After this peak, the wave of returning fish subsides and gradually declines until the end of the migration season (Figure 8c).

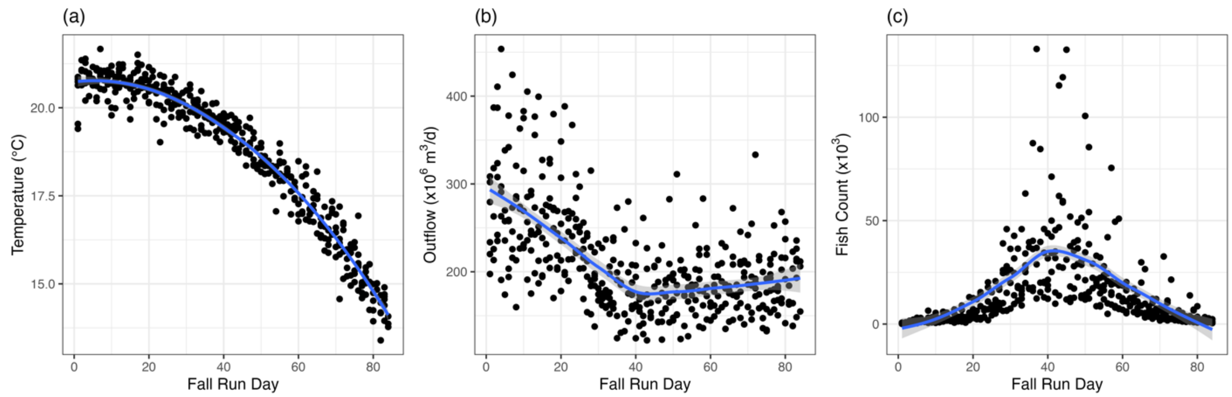

Figure 8. Long-term trends of the (a) water temperature; (b) discharge at the Hanford reach and (c) Chinook fish count observed at the McNary Dam. In each plot, the blue line represents the non-parametric locally estimated scatterplot smoothing (LOESS) smoothing of all the long-term observations from 1985 – 2024. Fall Run Days are the number of days since the beginning of the Fall Chinook migration on the 9th of August.

3.2 Relationship Between Fish Retention and Reach Temperature

The long-term temporal variation in fish retention in the Hanford Reach during the fall run (Figure 9a) is similar to that of the incoming fish count at McNary Dam (Figure 8c). This similarity is indicative of a significant correlation between incoming fish and fish retention with a correlation coefficient of 0.93 ($p < .001$) (Figure 9b). Therefore, an assessment of temperature and retention variation within the Hanford reach would likely be impacted by external factors, such as the ocean and downstream water environment, that affect the returning adult fish observed at the McNary Dam. On the other hand, the fish retention ratio showed a weaker correlation with the incoming fish count, with a correlation coefficient of 0.29 ($p < .001$) (Figure 9c). The retention ratio, normalized with respect to the incoming fish, provides a better alternative to assessing the effects of within-reach temperature variation at the Hanford Reach. By focusing on the normalized retention ratio, we can better evaluate the specific effects of temperature fluctuations within the reach, potentially leading to more targeted and effective management strategies.

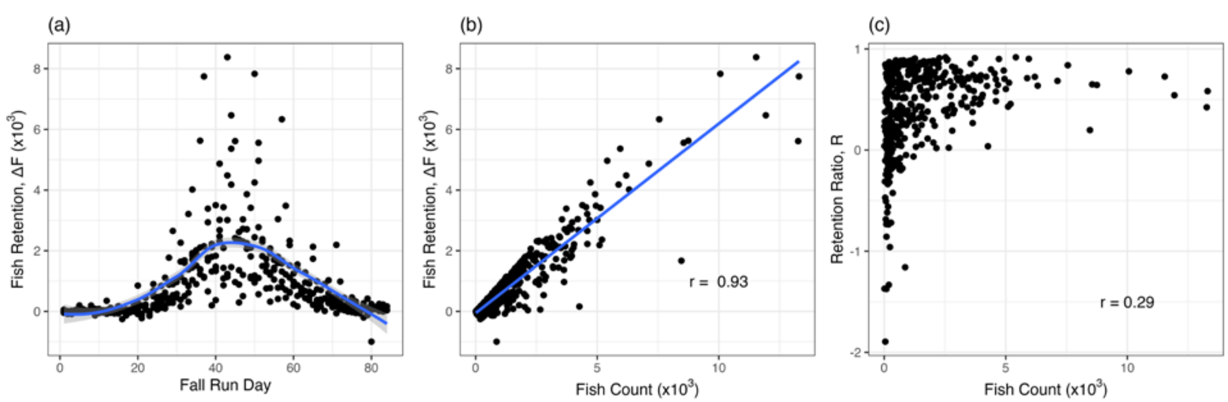

Figure 9. Assessment of the covariance between incoming fish count at McNary Dam and Fish Retention in the Hanford Reach: (a) long-term temporal variation of the fish retention; (b) 1-1

scatter plot of incoming fish count and the fish retention; and (c) 1-1 scatter plot of incoming fish and the retention ratio. Fall Run Days are the number of days since the beginning of the Fall Chinook migration on the 9th of August.

By using *R* as a metric for understanding fish behavior during migration, we observe a lower proportion of fish exhibiting stalling behavior within the Hanford Reach at the onset of the fall run (Figure 10a). This initial phase is characterized by minimal retention, indicating that most fish are actively migrating upstream. As the migration season progresses, *R* steadily increases, reaching a notable inflection point approximately 40 days into the season. This period is also accompanied by a broader range of *R* values, suggesting increased variability in fish behavior towards the latter part of the migration season. The relationship between R and the mean water temperature, when fitted with a LOESS line, reveals a trend that varies below and above an approximate threshold of 19 °C (Figure 10b). When the mean water temperature is below 19 °C, high retention ratios are predominantly observed. Beyond this thermal threshold, there is a decline in *R*, indicating that higher temperatures are inversely related to fish retention within the reach. This relationship between R and the mean water temperature underscores the importance of thermal conditions in influencing migratory patterns and a clearer historical picture that is comprehensive in space and time can only be derived from a tool like THORR. The observed decrease in retention ratio with rising temperatures suggests that fish are more likely to continue their migration rather than stall when exposed to warmer waters. Our ability to tease out this relationship using the spatially continuous temperature dataset from THORR highlights the tool's potential for reservoir-river management and application to understand fish dynamics.

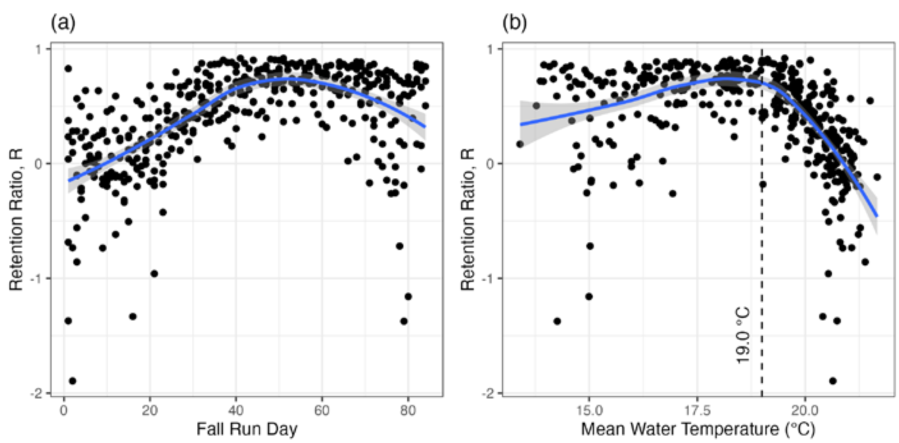

Figure 10. Long-term variations in the fish retention ratio (a) temporally as the fall migration season progresses and (b) compared to the mean water temperature at the Hanford Reach. In each plot, the blue line represents the non-parametric LOESS smoothing of long-term records from 1985 – 2024. Fall Run Days are the number of days since the beginning of the Fall Chinook migration on the 9th of August.

3.3 Interannual Variation of Mean Reach Temperature and Retention Ratio *R* in the Fall Migration Season

The interannual variation in the retention ratio tends to be linked to the thermal conditions within the Hanford Reach. For each year, we calculated the season's mean reach temperature and the total retention ratio *R* over the entire duration of the fall adult migration season. From 1985 to 2003, we observed a significant increase in the mean fall water temperature within the reach (Mann-Kendall trend test: $p = 0.006$; see Figure 11a). This trend suggests an approximate increase of 0.5 °C in fall water temperature (over 4 decades), with observations exceeding 19 °C becoming more frequent after 2010. Over the period from 1985 to 2023, there is a general decreasing trend in the retention ratio *R* at the reach (supported by the Mann-Kendall trend test $p < 0.001$; see Figure 11b).

The interannual variations indicate a clear relationship between increasing water temperatures and decreasing retention ratios. The variations further confirm the negative correlation between the retention ratio and water temperatures exceeding 19 °C within the reach as illustrated in Figure 10b. This negative correlation suggests that higher water temperatures, especially those exceeding 19 °C, adversely affect the retention ratio within the Hanford Reach. These findings underscore the importance of monitoring thermal conditions spatially over a reach to manage and preserve fish populations effectively.

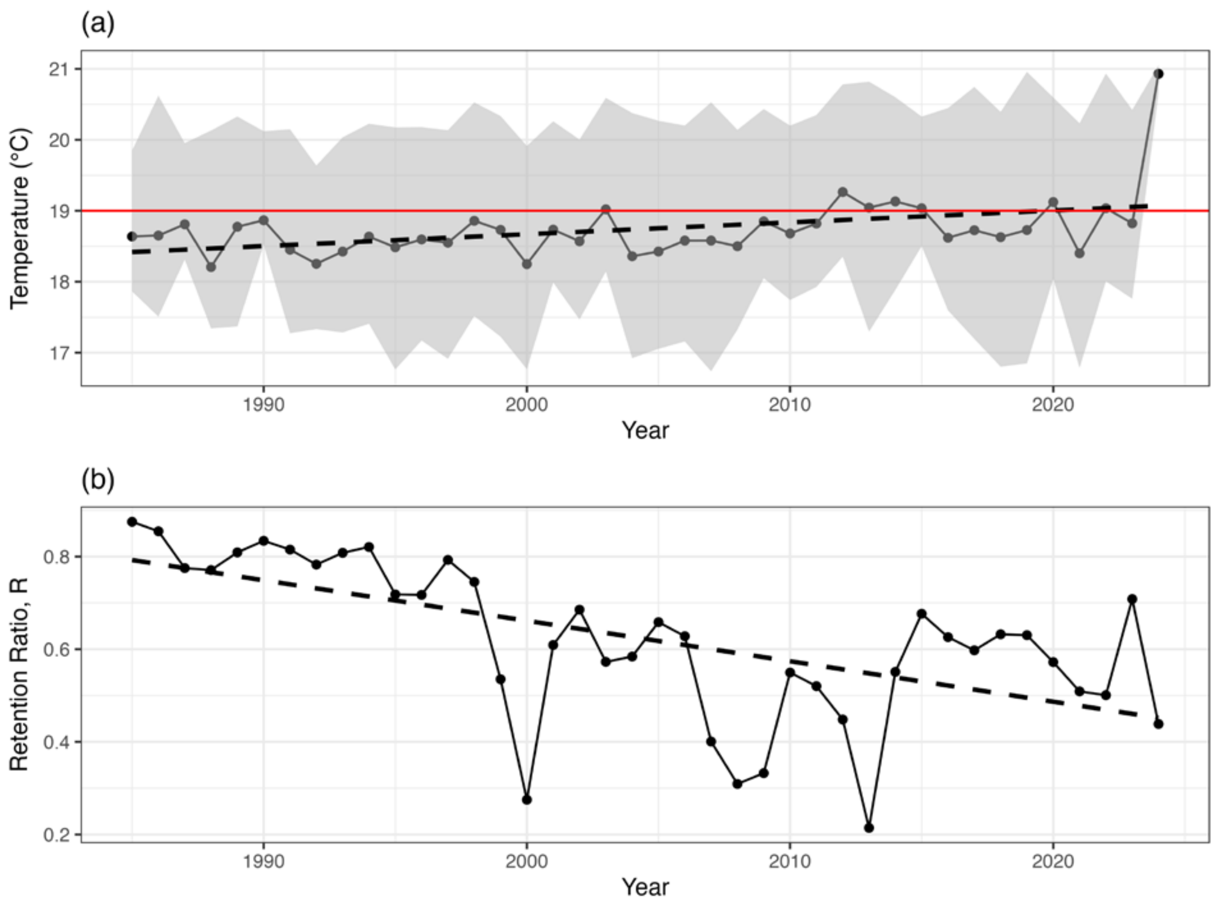

Figure 11. Interannual variation in the (a) mean fall water temperature within the Hanford Reach and (b) the total retention ratio at the Hanford Reach. The dashed lines indicate the trends in both the mean temperature (based on THORR) and retention ratio from 1985 – 2024. The shaded

region in (a) represents the 25th and 75th percentile bounds of water temperature within the reach.

4 Discussion

Climate change is a significant driver of rising riverine water temperatures, impacting the biodiversity of aquatic species (Comte & Grenouillet, 2013), altering predation rates (Petersen & Kitchell, 2001), and subjecting cold-water fish, such as salmon, to stressful and potentially lethal thermal conditions (Richter & Kolmes, 2005). However, controlled dam discharges in regulated rivers can potentially mitigate river warming (Michel et al., 2023). During warmer periods, lower-depth discharges from large, deep reservoirs tend to cool downstream river reaches due to thermal stratification (Bonnema et al., 2020; Gu et al., 1998; Olden & Naiman, 2010).

The beginning of the fall migration season at the Hanford Reach overlaps with the later parts of the warmer summer season in August. As shown in Figure 8a, and Figure 8b, the high temperatures observed within the reach at the beginning of the fall migration season are associated with high discharge from the Priest Rapids dam. This suggests that the operation strategies of the Priest Rapids dam do not result in downstream cooling during the warmer beginning of the fall migration season despite high discharge. Historically, summer discharge from the Priest Rapids Dam includes more than 39% of the spill from the top pool of the reservoir, according to the Grant Public Utilities Department (Grant PUD), managers of the dam (see Figure S1 in the Supporting Information). Moreover, after the completion of the fish bypass infrastructure at the dam, the turbine discharge is reduced to aid fish passage through the turbines while balancing the discharge with a spill to meet the flow requirements in the fish bypass infrastructure (Grant PUD, n.d.). The spill transfers warmer water downstream which reduces the effectiveness of downstream cooling by lower-depth discharges through the turbines. Therefore, based on THORR's spatial overview of the downstream water temperature in the Hanford reach, it may be necessary to reduce the proportion of spills in the warm season to ensure optimal thermal conditions for the migrating fish.

Dam managers need to consider the effects of warm spills on downstream water temperature. However, dams that prioritize hydropower generation through turbine flow tend to dampen the downstream water temperature. In such cases, dam management options, such as multi-level withdrawal and draft tube mixer, can help to bring the downstream water temperature closer to the natural thermal regime, similar to upstream conditions (Olden & Naiman, 2010). However, in the absence of such management options, which may require dam retrofitting, managers can adjust the percentage of the spill to optimize the downstream water temperature while meeting other dam requirements, such as hydroelectric power production. THORR's spatial temperature estimates can provide upstream and downstream information, useful in determining the proportion of spill needed to reduce the downstream cooling effect. See Table S1 and Figure S2 of the Supporting Information for an example of how to improve downstream water temperature based on upstream and downstream temperature information.

The spatiotemporal water temperature data obtained from the THORR dataset reveal distinct effects of dam operations on downstream fish compared to those observed upstream. Specifically, discharge-focused operations at the Priest Rapids Dam result in a greater percentage of fish traveling upstream of the Hanford Reach. This is indicated by the low *R* values observed when water temperatures are high at the beginning of the fall migration season (Figure 10). The increase in the proportion of fish migrating upstream could be linked to the fish's swimming performance, which is influenced by the water temperature at the Hanford Reach. Some studies based on laboratory simulations and observations have shown that the swimming speed of juvenile salmon (Brett et al., 1958; Griffiths & Alderdice, 1972) and the swimming performance of adult salmon (Korus et al., 2024; Lee et al., 2003) increase with increasing water temperatures. However, we acknowledge that an alternative, probable explanation for our finding could be that the fastest fish are merely the first to arrive at the Hanford Reach, coincidentally at a time when the temperature is high. But we are unable to prove this alternative explanation within the scope of our study, since such an assessment would require an extensive tracking of fish from the ocean to the Hanford Reach.

Using PIT tag data from 2,767 adult Chinook salmon observed in the Hanford Reach from August 2003 to October 2024, we found that the mean swim speed, expressed as the inverse of the time (in days) between observations at the inlet of the reach (McNary Dam) and the upstream outlet of the reach (Priest Rapids Dam), tends to be highest at the beginning of the fall migration season and decreases over time (Figure 12a). As water temperature increases between the range of 19 °C and 21 °C, the swim speed also increases correspondingly (Figure 12b). This trend aligns with laboratory findings, as the water temperature within the reach is highest at the beginning of the fall migration season. The THORR-based temperature dataset that is continuous in space and time has demonstrated for the first time, to the best of our knowledge, the validation of laboratory findings in a real-world setting of the Hanford reach. Above lethal water temperature levels (> 21 °C), Goniea et al. (2006) found that the migration rate of fall Chinook salmon reduces since they retreat into cold refugia. Below sub-lethal temperature, instead of a complete halt, the fish either retreat into cold refugia in tributary plumes or "continue to migrate through stressful thermal conditions" (Goniea et al., 2006, p. 415). Our assessment of THORR's spatially averaged water temperature in the Hanford Reach sheds some light on the migration behavior of the fall Chinook salmon below sub-lethal thermal conditions. The relationship between high water temperature (below lethal thermal conditions) and high swimming speed could explain the low R values observed at the start of the migration season. One thing to note, however, is that our analysis and findings are based on river temperature estimates and quality-controlled fish count data. Both data sources have inherent limitations at a sub-reach scale. However, at a macro level, they can be representative of reach-scale phenomena such as migration.

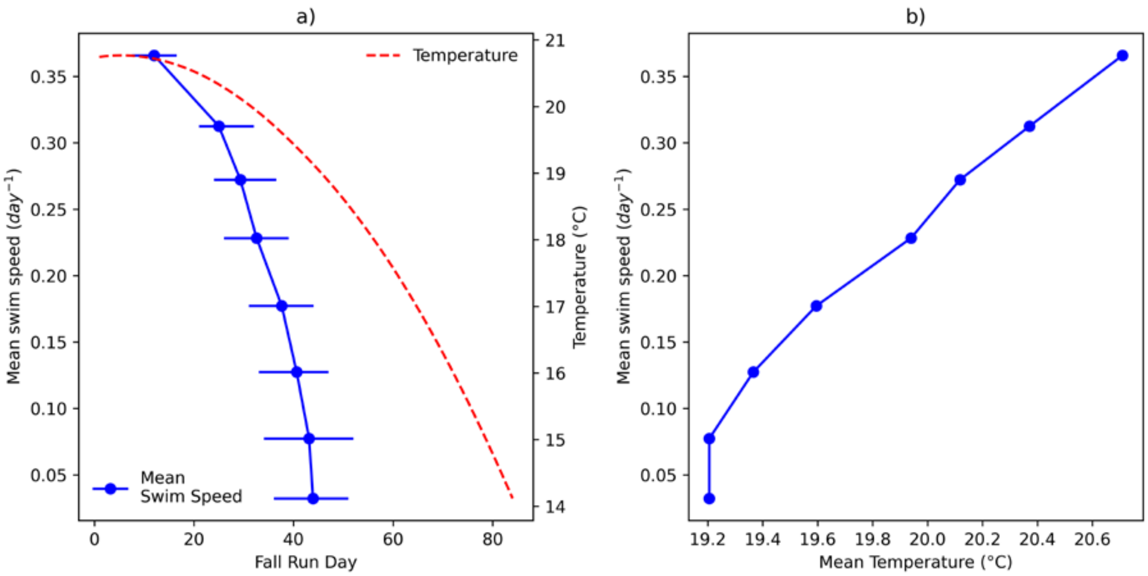

Figure 12. Relationship between swim speed and water temperature. a) Temporal variation of adult Chinook fish swim speed and mean water temperature in the Hanford Reach; b) Direct relationship between the mean swim speed and the mean water temperature in the Hanford Reach. The horizontal bars represent the range of days on which the 25th to 75th percentile of the fish was observed at the indicated mean swim speed. The variations represent the long-term mean temperature during the fall migration season from 1985 – 2024. Fall Run Days are the number of days since the beginning of the Fall Chinook migration on the 9th of August.

While high proportions of fish observed upstream may indicate the effectiveness of dam operations and infrastructure that support fish passage, the resulting absence of downstream cooling may conversely signal the negative impacts on fish whose natal destination is below the dam. In the Hanford Reach, the water temperatures consistently exceeded 19°C and often surpassed 20°C during the first 30 days of the fall migration season (Figure 8a), despite temperatures above 19-20°C being stressful for adult Chinook salmon (Connor et al., 2019; Keefer et al., 2018).

The increasing trend in water temperature in the Hanford Reach that THORR has depicted now warrants attention to river regulation that considers downstream water temperature. Over the past decade, the mean fall water temperature in the Hanford Reach has exceeded the stressful threshold for Chinook salmon more times than before (Figure 11a). Without intervention, this trend suggests that water temperatures will likely exceed lethal thresholds more often, endangering Chinook and other cold-water species within the reach. Interventions balancing discharge and temperature requirements can ensure a stable retention ratio while maintaining optimal conditions for fish survival in the downstream reach. Such a balanced intervention is in operation in the CRB at the Dworshak Dam along the Snake River (Connor et al., 2019).

The insights we highlighted here on the thermal trend underscore another potential of THORR in understanding long-term riverine temperature patterns that can be extended to other reaches and seasons of choice.

5 Conclusion

Water temperature is a critical factor influencing the survival and migration of fish. While river regulation can alter the thermal regime of rivers, it also provides an opportunity to intentionally adjust conditions through dam operations to benefit fish and other aquatic organisms in the riverine ecosystem. Achieving a balance between reservoir discharge and temperature requirements is essential to facilitate fish passage and sustain downstream ecosystems. However, dam operations often prioritize discharge requirements for fish, likely due to the lack of spatiotemporal riverine water temperature data needed to assess the potential temperature impacts of dam operations downstream. By leveraging THORR's continuous spatiotemporal river temperature estimates that are otherwise not available from in-situ probes or thermal modeling, we assessed the dynamics of water temperature in the Hanford Reach and how these variations relate to fish abundance and migration patterns.

Our findings indicate a projected increasing trend in water temperature at the Hanford Reach, surpassing stressful and lethal thresholds for cold-water fish. We also identified that high temperatures downstream of a dam may cause a higher proportion of fish to travel upstream at faster speeds. Monitoring fish counts at dam locations may provide a misleading signal regarding the effectiveness of discharge-focused reservoir operations, as unmonitored water temperatures in the downstream reach could have detrimental effects on fish. Spatiotemporal estimates from THORR reveal the potential thermal implications of upstream dam operations. Despite the new data-driven insights on fish offered by THORR's spatiotemporal temperature estimates, there are a few limitations to this study worth noting: The mass balance approach to fish abundance and retention uses recorded fish counts at the inlets and outlets of the Hanford Reach. However, fish counts within the reach to quantify impacts that are disruptive to fish abundance, such as fishing and mortality, were not included. At the time of our study, the Washington Department of Fish and Wildlife had published annual fishing reports from 2012 to 2021. Although the data in these reports encompasses abstraction within the Hanford Reach, we did not include abstraction in analyses because the impacts of abstraction due to sports fishing are negligible enough to the overall data-driven findings of our study, which demonstrate the water management value of a tool like THORR (see Figures S3 and S4 in the Supporting Information).

A reach-scale assessment, such as the one presented in this study, is now possible with THORR's extensive spatiotemporal water temperature estimates. In this study, we aimed to highlight the general potential of THORR as a tool for understanding fish patterns from a reservoir management perspective. However, fish are just one aspect of the potential applications of THORR. Other potential uses include assessing the impact of climate change on river temperature and evaluating aquatic conditions such as harmful algal blooms. THORR's scalable nature, based on remote sensing and data-driven techniques, makes it a valuable tool for long-term basin-wide assessments. Future considerations include extending this study to assess spatial variations in fish and water temperature dynamics at the basin scale. Additionally, we plan to incorporate other scalable discharge tools, such as the satellite-based Reservoir Assessment Tool (RAT; Minocha et al., 2024), to determine the direct influence of reservoir discharge on ungauged riverine ecosystems of the world.

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Open Research

The data and code used in this study are available at https://doi.org/10.5281/zenodo.14291483 (George Darkwah, 2024). The THORR tool used for estimating the water temperature is available at https://depts.washington.edu/saswe/thorr. The fish count data are public-domain and available from CBR-DART:
Visual counts of adult fish: https://www.cbr.washington.edu/dart/query/adult_graph_text
PIT Tag observations: https://www.cbr.washington.edu/dart/query/adult_graph_text
The in-situ discharge data used in this study is also public domain and accessible from CBR-DART at https://www.cbr.washington.edu/dart/query/river_daily

Author role:

George K. Darkwah – research design, data, implementation, analyses and manuscript writing
Faisal Hossain – research supervision, analyses, manuscript editing and reviewing

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