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Drought and reservoir drawdown: implications for bull trout distribution and passage

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Abstract Bull trout (*Salvelinus confluentus*) are a species of char listed as threatened in the United States under the Endangered Species Act. Two critically depressed populations persist in Kachess Reservoir of the upper Yakima River Basin in Washington State. Due to proposed changes in water management and the lack of information on the movement ecology of bull trout in Kachess Reservoir, we initiated this study to better understand these populations. We used acoustic telemetry to describe spatiotemporal movements of bull trout, identify barriers to movement across a constricted passage corridor in the reservoir called The Narrows, and define correlates of depth distribution. Our study spanned both non-drought (2022) and drought (2023) years as defined by the state of Washington, between which the water surface elevation in Kachess Reservoir varied substantially. Bull trout distribution shifted south in 2023, with most fish moving south of The Narrows by mid-summer. While movements across The Narrows in both directions occurred throughout 2022, no bull trout crossed The Narrows after July 2023, suggesting that lower water levels resulted in barriers to movement. Bull trout depth distribution showed significant, consistent diel vertical migrations, while average depths were similar across years. With more lentic habitat located south of The Narrows, but both spawning tributaries only accessible north of The Narrows, it is essential to maintain passage for bull trout across this corridor to ensure access to spawning tributaries.

Keywords Fish ecology · Biotelemetry · Salmonid movement · Bayesian modeling · *Salvelinus confluentus*

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Introduction

Bull trout [*Salvelinus confluentus* (Suckley, 1859)], a species of char historically distributed through the Northwest United States and Canada, can display anadromous, adfluvial, fluvial, or resident life histories (Rieman and McIntyre 1993; McPhail and Baxter 1996). Bull trout populations often co-occur with numerous other salmonid species but have particularly stringent requirements for cold, connected habitat (Selong et al. 2001), generally using temperatures less than 13 °C for spawning and

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rearing and 14 °C for foraging and migrating (Jones et al. 2014; Gutowsky et al. 2017). These thermal requirements along with spawning and foraging behavior are thought to be the main drivers of bull trout movements. Diel vertical migrations have been observed in adfluvial populations and are a function of feeding opportunity, physiological constraints, and predator avoidance, especially earlier in ontogeny (Gutowsky et al. 2013; Eckmann et al. 2016). Potamodromous populations undergo migrations in summer from lakes (adfluvial populations) or larger rivers (fluvial populations) to headwater tributaries to spawn, and in some circumstances, to seek thermal refuge (Maret and Schultz 2013). Population declines and extirpations are widespread throughout their range (McPhail and Baxter 1996) and are often linked to changes in land and water management (Rieman et al. 1997), invasive species (Leary et al. 1993), and historical overfishing (Mongillo 1992). Declines in most bull trout populations led to their designation as threatened under the Endangered Species Act in 1998 (USFWS 2024). Climate models predict that changes to stream temperatures and flow regimes will further fragment habitat and reduce bull trout populations (e.g., Rieman et al. 2007), especially in the southern and interior portions of their range.

Historically, the Yakima River Basin (YRB) supported 15 populations of bull trout, 3 of which are now extirpated. The 12 remaining populations persist in higher elevation headwater streams, rivers, and lakes, including 7 adfluvial populations that reside within impounded reservoirs and their tributaries. Kachess Reservoir, in the upper YRB, hosts two bull trout populations that were designated as critically depressed in 2004 (WDFW 2004) and have seen low redd counts (2020–2024 average: 9.4 in Box Canyon Creek, 7.2 in Kachess River) during regular surveys in the last three decades (James 2002; Divens 2023). These populations have been the focus of habitat enhancement work in recent years, with over $4 M US invested in increasing instream complexity, creating side-channel habitat, and reconnecting the floodplain in the upper Kachess River (Kittitas Conservation Trust 2023). Climate projections suggest that by the end of the twenty-first century, the YRB will experience reduced snowpack and earlier runoff (Elsner et al. 2010; Wagner et al. 2021), resulting in diminished cold-water inputs that historically extended through the fall and maintained water temperatures within the preferred range of bull trout (Selong et al. 2001).

The YRB is home to the largest agricultural economy in Washington State, producing over half of the nation's hops, apples, and cherries which generate $4.5 B US annually. Agriculture in the basin is heavily dependent on irrigation, such that a complex network of reservoirs, diversions, and canals exists to meet these demands (WDOE 2015). Water is stored and conveyed within the Yakima Project, a series of dams and reservoirs in the basin, which is owned and operated by the US Bureau of Reclamation (USBOR). Current reservoir operations create two primary threats to adfluvial bull trout populations in the YRB. First, entrainment through dams without upstream fish passage limits access to spawning tributaries. Second, falling pool elevations during the irrigation season, which coincides with the timing of spawning migrations, can create impassable conditions at tributary mouths due to channel braiding over the exposed lakebed (Josh Rogala, WDFW, pers. comm.).

The YRB has historically been prone to drought, but drought frequency and severity are increasing. The Washington State Department of Ecology has issued drought declarations for the upper Yakima River in 9 of the last 40 and 6 of the last 11 years (Fig. 1). Drought strains water supplies which are jointly managed for irrigators as well as fish and wildlife under the Yakima Basin Integrated Plan. Increased frequency of drought and water demand may result in reduced water allocations to agricultural and municipal users (Vano et al. 2010), while also

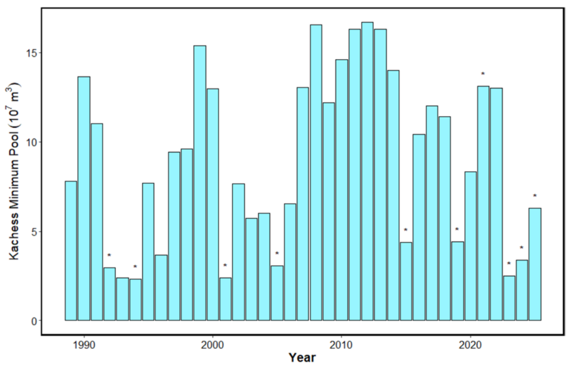

Fig. 1 Kachess Reservoir minimum pool level, 1989 to 2025. Asterisks above bars represent years in which the Washington Department of Ecology issued formal drought declarations for the upper Yakima River including Kachess Reservoir

creating or worsening passage barriers at the mouths of bull trout spawning tributaries (Beebe et al. 2025). To increase water accessibility during drought years, the USBOR proposed the Kachess Drought Relief Pumping Plant (KDRPP), which could access up to 2.46×10^8 m^3 (200,000 acre-feet) of dead storage below the current minimum low pool in Kachess Reservoir (USBOR and WSDOE 2018). The operation of KDRPP could decrease reservoir productivity through earlier, longer, and larger drawdowns. In nearby Keechelus Reservoir, Hansen et al. (2017) found that earlier-timed drawdowns limit benthic-littoral production. The same study observed that while Kachess Reservoir appears to have the energetic capacity to support larger bull trout populations under current management, numbers remain low. This may be attributable to spawning and rearing habitat access during low water years, which could be further restricted under KDRPP.

Our objectives were to describe the vertical and horizontal distribution of bull trout within Kachess Reservoir. We then compared bull trout movements during drought and non-drought years and inferred the potential implications of KDRPP on bull trout movement in the system. Finally, we examined bull trout passage through The Narrows, a constricted corridor that separates the two lake basins within Kachess Reservoir during low water conditions, which could limit bull trout access to the upper lake basin and spawning tributaries as water levels recede.

Methods

Study location

The Yakima River of south-central Washington State drains the eastern slope of the Cascade Mountains, flowing southeast 344 km before joining the Columbia River. Snowmelt and glacial runoff are the main contributors to flow in the system, which drains roughly 15,800 km^2 from high elevation alpine habitats along the headwaters through subalpine, montane, and foothill shrub-steppe desert habitats until reaching the Columbia River roughly 520 km from the Pacific Ocean. The YRB has five major storage reservoirs—Rimrock and Bumping in the Naches River Basin; and Keechelus, Kachess, and Cle Elum in the upper YRB. Kachess Reservoir, historically two natural lakes (Big Kachess and Little Kachess) connected by a portion of the Kachess River, was impounded in 1912 by Reclamation to increase water storage for irrigation. The current reservoir level can fluctuate 21 m between full pool at 689 m water surface elevation (WSE) and minimum low pool at 668 m WSE (Fig. 2). Big and Little Kachess become distinct lakes connected by a channel called The Narrows at 678 m WSE, while at 672 m WSE, fish passage across The Narrows becomes

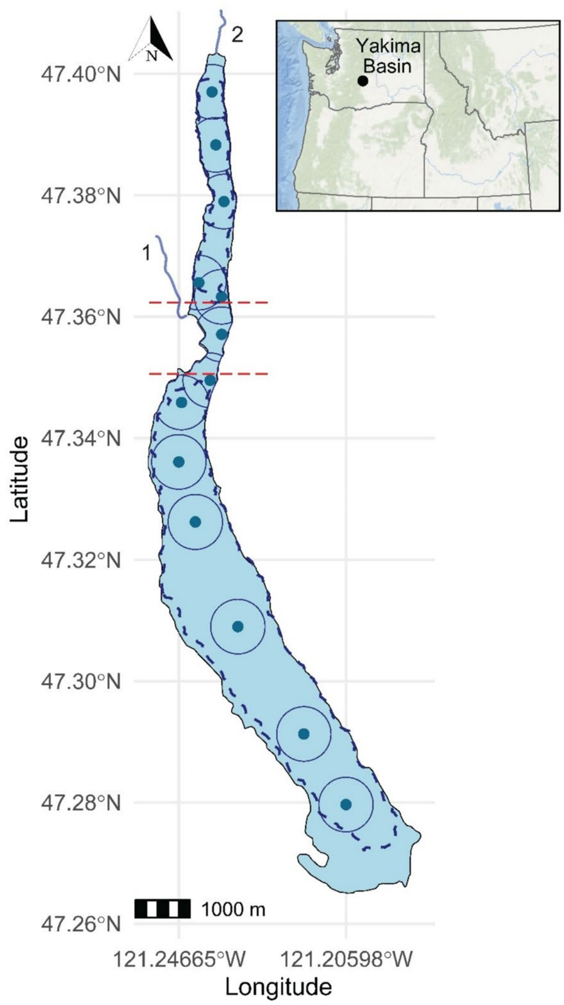

Fig. 2 Map of Kachess Reservoir within the Yakima River Basin, showing the locations of 13 VR2W or VR2Tx acoustic receivers (blue points) and associated 500-m detection buffers (blue circles). The red lines indicate the upper and lower bounds of The Narrows. The numbered blue lines show the two bull trout spawning tributaries in the system: (1) Box Canyon Creek and (2) Kachess River. The reservoir outline is representative of full pool conditions, while the dotted line shows 2023 low pool (670.6 m WSE)

limited (Fig. 3). If implemented, KDRPP could result in an additional drawdown of up to 25 m, creating a new low pool level at 643 m WSE. Peak WSE is typically seen in mid- to late-June just before discharge from the dam outpaces snowmelt inflow, while minimum WSE tends to occur in mid-October when discharge for agricultural purposes is curtailed. Our study occurred from 2022 to 2023 due to the disparity in reservoir storage between these years and our interest in the response of bull trout to these conditions. Reservoir storage in 2022 was consistent with non-drought years in the previous decade, with 99% capacity at high pool and 44% capacity at low pool. Storage in 2023 was consistent with drought conditions and aligned with a drought declaration from Washington state, with 85% capacity at high pool and 9% capacity at low pool (https://www.usbr.gov/pn/hydromet/yakima/). Box Canyon Creek and the Kachess River (Fig. 2) are the only tributaries in the system with spawning bull trout populations. These populations are adfluvial and migrate into spawning tributaries in late summer to fall, but the timing and success of these migrations vary due to intermittent stream flow (Beebe et al. 2024, 2025). In general, bull trout enter Box Canyon Creek as early as July, while the Kachess River is inaccessible until fall rains significantly increase flow because the river goes sub-surface in summer, creating a fish passage barrier.

Tagging and tracking

To document the spatiotemporal distribution of bull trout in Kachess Reservoir, we tagged and released 36 juvenile bull trout with V9-2x ($n = 16$; 690-day tag life; 27.5×9 mm; 4.5 g in air; 2.7 g in water; 90-s mean delay) or VTP9-2x ($n = 20$; 569-day tag life; 31×9 mm; 4.9 g in air; 2.8 g in water; 90-s mean delay) transmitters (Innovasea, New Bedford, Nova Scotia, Canada). Fish were released in July of 2021 ($n = 15$) and 2022 ($n = 21$). The VTP9 tags transmit depth and temperature data recorded by the internal tag at the time of transmission, allowing

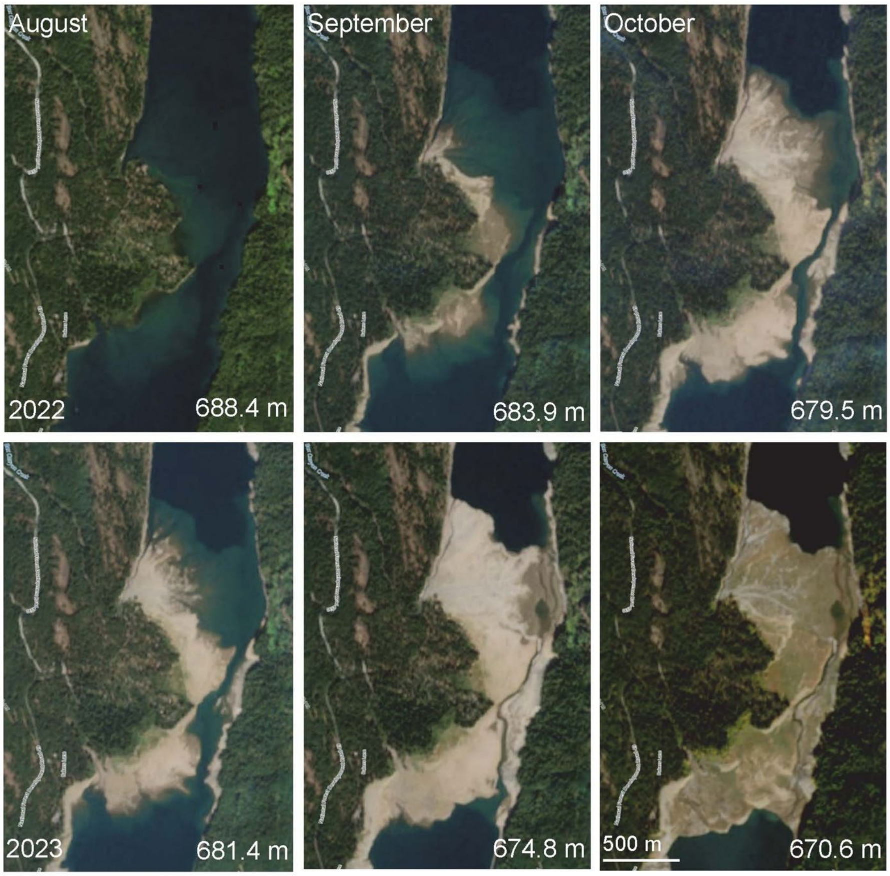

Fig. 3 Monthly satellite images of The Narrows from August through October in 2022 (top row) versus 2023 (bottom row). Water surface elevations for the respective date are listed in the bottom right-hand corner of each photo. The Narrows forms at 678 m WSE and volitional fish passage ceases at 672 m WSE. Satellite imagery available online at https://browser.dataspace.copernicus.eu/

for the collection of detailed depth and temperature data. Yakama Nation Fisheries provided fish for tagging through a collaborative rescue-rear program. This program rescues young-of-year bull trout from disconnected pools in the Kachess River, the lower part of which dewaters during summer and early fall. Fish are artificially reared over the winter in holding tanks and released north of The Narrows into Little Kachess the following summer. Fish size at tagging ranged from 252 to 396 mm total length (TL) in 2021 and 270 to 310 mm TL in 2022. Fish were held for 1-week post-tagging to ensure recovery, tag retention, and survival. Adfluvial bull trout within the YRB grow roughly 100 mm per year until age 5 (Connor Cunningham, USFWS, unpublished data), suggesting that 2021 tagged fish would range from 409 to 540 mm TL at the end of their tag life and prior to the study ending, while the 2022 tagged fish would range from 418 to 448 mm TL when this study ended in December of 2023. These ranges fall within the published length at 50% maturity of 424 mm TL for adfluvial bull trout (McCubbins et al. 2016), indicating that during our study, fish may have sexually matured.

We maintained an acoustic array comprised of four VR2W and nine VR2Tx receivers throughout the study (Fig. 2). We deployed receivers in both Little and Big Kachess to examine fish distribution and movement throughout the reservoir, with a higher density of receivers adjacent to The Narrows. We fastened receivers to a line between an anchor and subsurface bullet float to maintain the vertical orientation of the receiver, with a surface buoy attached. We downloaded data monthly throughout the summer and fall and opportunistically in the winter and spring when snow and ice cover allowed. Tag tests indicated a detection range of about 500 m for both receiver models prior to releasing tagged fish (Taylor 2022).

Data management and analyses

Two years (2022, 2023) of acoustic detections from bull trout were filtered before analysis. For each fish, we created plots with depth and location through time to determine if a fish displayed behavior consistent with mortality or a tag shedding event, shown as consistent depth and location transmissions for the remaining extent of the tag life. For fish that exhibited the aforementioned behaviors, we truncated data to the last known transmission from the fish while assumed to be alive. We also removed the first week of detections from each fish to account for any potential unnatural behavior following release (Rogers and White 2007; Gutowsky et al. 2016, 2017). Finally, we omitted single transmissions without another in the previous or following hour, which are often considered a sign of an erroneous detection. Of the 15 fish tagged in 2021, 10 were classified as a mortality or shed tag before the commencement of this study and were omitted from analyses. Likewise, six of the 21 fish released in 2022 were removed from the dataset by filtering due to mortality or shed tag within a week of release. For seasonal analyses, we binned data into four seasons: winter (January–March), spring (April–June), summer (July–September), and fall (October–December). We tracked crossings of The Narrows by binning receivers from Big and Little Kachess, such that any detection in Little Kachess followed by a detection in Big Kachess (or vice versa) was deemed a crossing of The Narrows. The single receiver located within The Narrows was not included in either of the bins to ensure distinction between the two lakes. For the nine individuals with VTP9 tags, depth and temperature data were averaged by hour for each fish to standardize the individual contribution in the data analyses. The averaged hourly data were used to produce average seasonal depth and temperature summaries (Table 1). All data management and analyses were conducted in R v4.2.3 (R Core Team 2024).

We simulated a two-dimensional correlated random walk (CRW) to generate realistic movement paths for acoustically tagged bull trout between detection events. In passive acoustic telemetry, the position associated with a received tag transmission is typically the receiver location and not the actual location of the tag. Applying a CRW to detection data allowed us to generate probable locations based on known fish behavior (e.g., swimming speed and direction). Although estimated, the constructed data represent more realistic fish behavior than placing the fish at the receiver location repeatedly. The CRW model accounts for both directional persistence and stochastic variation in step lengths and turning angles, which better reflects the autocorrelated nature of animal movement compared to models assuming independent locations (Johnson et al. 2008). For each individual movement event, a random starting location was

Table 1 Mean (±SD) and median (range) water depths (m) and temperatures (°C) transmitted by internal sensors in summer and fall in 2022 and 2023 from tagged bull trout. Sample size varies by season due to fish mortalities or tag life expiration. High individual depth variability resulted in skew as is reflected by large standard deviation values

Year	Season	Number of fish	Mean (SD) Depth (m)	Median (range) Depth (m)	Mean (SD) Temperature (°C)	Median (range) Temperature (°C)
2022	Summer	7	19.3 (25.0)	10.4 (0–120.4)	9.7 (3.2)	10.2 (3.6–20.0)
	Fall	6	15.4 (24.8)	7.2 (0–103.3)	4.9 (2.2)	4.1 (0–16.1)
2023	Summer	3	13.1 (8.9)	11.4 (0–45.1)	9.2 (3.0)	9.0 (4.1–18.0)
	Fall	3	8.7 (25.0)	5.3 (0–67.0)	7.1 (2.4)	6.2 (3.7–12.5)

selected within the 500-m detection buffer around the receiver. Successive positions within the buffer were generated using step lengths drawn from a Weibull distribution and turning angles from a wrapped Cauchy distribution. The resulting displacement was applied iteratively to the previous location. All candidate positions were constrained to fall within the 500-m buffer and known in-water areas by testing spatial intersection between receiver detection buffers and the reservoir boundary. This approach preserves both the tortuosity and spatial constraints of fish movement in complex aquatic environments.

We then used the simulated movement paths generated by the CRW to estimate kernel utilization distributions (KUDs), which describe the probabilistic space use of fish over time (Samuel et al. 1985). Although KUDs are widely used for estimating animal space use, they assume that location data are independent and identically distributed—an assumption often violated by acoustic telemetry data due to temporal autocorrelation and irregular sampling (Kraft et al. 2023). By using CRW-simulated data as the input, we accounted for these characteristics and produced more realistic estimates of space use (Johnson et al. 2008). KUDs were generated using the kernelUD function from the adehabitatHR package (Calenge 2006). A fixed-bandwidth kernel density estimation was performed on a 100-m resolution grid to estimate the intensity of space use across the study area. Probability contours representing the 50% (core use) and 95% (home range) utilization distributions were extracted for visualization and to quantify core area overlap across years and seasons, enabling assessment of spatiotemporal shifts in distribution. This analysis focused on summer and fall seasons for two primary reasons: (1) higher water temperatures and spawning migrations during these periods typically result in increased fish activity, and (2) fish from the 2022 cohort were released in July and thus only in the system for summer and fall of 2022, providing the greatest data availability for cross-year comparisons.

To investigate the factors influencing bull trout depth distribution, we fit a Bayesian hierarchical model using the brms package (Bürkner 2017). This approach fits a linear model that accounts for temporal autocorrelation, hierarchical structure, and uncertainty, providing a robust framework for interpreting depth use patterns. The model included data from all seasons and was estimated using Hamiltonian Monte Carlo with three chains of 3000 iterations each, including a 1000-iteration warm-up. A correlation structure was included to account for the temporal autocorrelation that is characteristic of acoustic telemetry data. The response variable was the natural logarithm of average hourly depth, modeled with a Gaussian link as a function of both fixed and random effects. Fixed effects included: (1) daylight (day vs. night), (2) scaled average hourly temperature at 15 m depth (as a proxy for thermocline presence), and (3) scaled water surface elevation at the time of observation. Random effects accounted for variation across individual fish, year, and receiver station. We assessed multicollinearity among predictors using variance inflation factors (VIF), and model convergence using R-hat values. Model selection was guided by leave-one-out cross-validation (Vehtari et al. 2017), with the final model chosen based on minimized information criteria and patterns in the residuals.

To characterize seasonal changes in water temperature and identify the thermocline, we deployed a series of temperature loggers (Onset, Bourne, Massachusetts) at depths of 1, 5, 15, 25, and 50 m on a buoyed logger string anchored to the bottom of the reservoir. The logger string was deployed just south of The Narrows at a depth of about 60 m with loggers set to record every 15 min and was active through the entirety of the study. WSE for Kachess Reservoir was accessed from the USBOR's Hydromet Real-Time Data Access site (https://www.usbr.gov/pn/hydromet/yakima/yakwebdayread.html). The R package suntools (Bivand and Luque 2024) was used to separate fish detections into blocks of day or night based on sunrise and sunset times.

Results

Filtering of the raw detection data ($n = 5,924,042$ detections) yielded 3,024,433 filtered detections from 20 individuals (9 V9TP, 11 V9). There was an average of 451 days between first and last detection and a 92% array residency. Bull trout used deeper habitat on average in summer compared to fall in both years, with median ($\tilde{x}$) depths below 10 m which corresponded with median temperatures of 9–10 °C (Table 1). They also used shallower habitat on average at night ($\tilde{x} = 6.0$ m) compared to daytime ($\tilde{x} = 11.3$ m), but the difference in day and nighttime depths varied substantially by season. The greatest differences between day and nighttime depths were observed in spring ($\tilde{x} = 8.4$ m) and winter ($\tilde{x} = 5.9$ m), followed by fall ($\tilde{x} = 4.7$ m), with little difference between summer ($\tilde{x} = 1.4$ m) day and nighttime depths (Fig. 4), both of which exceeded 10 m.

Kernel utilization distributions revealed that core area and home range were similar in size across years for summer and fall seasons (Table 2). However, core area shifted south for both summer and fall in the 2023 drought year when compared to 2022 (Fig. 5), resulting in increased use of Big Kachess as core area in 2023. Core area overlap was 42% between summer of 2022 and 2023, and 23% between fall of 2022 and 2023, illustrating the distinction in areas used between years.

Bull trout crossed The Narrows throughout each season in 2022, while August through December of 2023 yielded no crossings (Table 3; Fig. 6). Winter crossings were comparable across years; however, spring crossings were much lower in 2022 (11) than in 2023 (51). The minimum WSE in the summer of 2022 (681.8) and spring of 2023 (682.8) was similar and aligned with the highest number of Narrows crossings for their respective years, which may indicate that there is a threshold WSE at which bull trout more commonly pass through The Narrows. Minimum WSE in the summer and fall seasons of 2023 was approximately nine m lower than the same time periods in 2022. These lower minimum WSEs in 2023 stretched well below the 678 m WSE threshold at which The Narrows are considered to form a river-like channel and dropped 1.2 m below the 672 m WSE threshold at which volitional fish passage across The Narrows is believed to no longer exist.

The Bayesian generalized multivariate model indicated that bull trout depth is strongly positively correlated with daytime, and to a lesser extent, temperature and WSE (Table 4). Year did not have a strong effect on depth distribution. There was strong variation in depth distribution across individuals (52.1% variance explained) and stations (31.5% variance explained). The model predicted an average daytime depth of 8.25 m, with average nighttime depths 62% of daytime depths (Table 4). The Bayesian conditional r^2 value for this model was 0.39.

Discussion

The inability of bull trout to cross The Narrows during low water could limit their access to spawning grounds in the Kachess River and Box Canyon Creek, tributaries of Little Kachess. During the drought in 2023, core area shifted south of The Narrows into Big Kachess, and no bull trout crossed The Narrows after July of 2023, suggesting that fish in Big Kachess became isolated from their spawning grounds. The Narrows became impassable as WSE dropped below 672 m in October of 2023, but likely became a thermal barrier before then. A thermocline typically develops in Kachess Reservoir in late June and remains through September (Hansen et al. 2017; USFWS, unpublished data). Surface water temperatures during stratification can exceed 20 °C and limit the use of shallow habitats by bull trout. During the summer of 2023, bull trout experienced a median water temperature of 9 °C and a depth of 11.4 m (Table 1). Water temperatures in 2023 exceeded 10 °C at 15 m depth for 94% of days from July 1 to October 8 (USFWS, unpublished data), when WSE dropped below the 672 m threshold and a passage

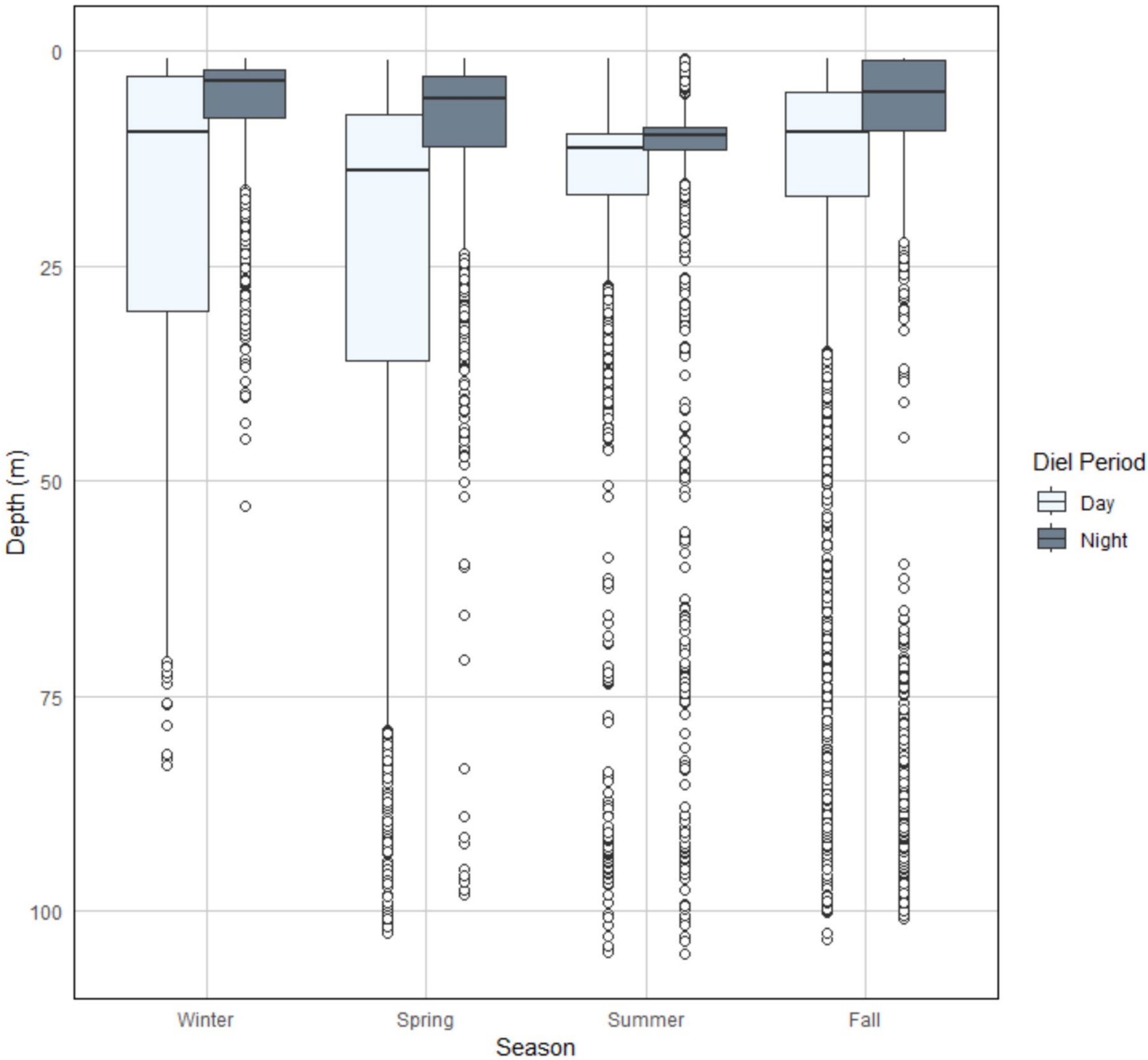

Fig. 4 Diel depth distribution of all V9TP tagged bull trout by season during 2022 and 2023

Table 2 Core area and home range of tagged bull trout in summer and fall during 2022 and 2023

Year	Season	Core Area (km^2)	Home Range (km^2)
2022	Summer	3.48	10.0
	Fall	3.71	10.1
2023	Summer	3.66	13.0
	Fall	3.66	13.1

barrier formed. When the last bull trout crossed The Narrows at the end of July 2023, the water depth was approximately 12 m and then quickly decreased to 9.5 m by August 18 when the entire water column would have exceeded 18—19 °C (Hansen et al. 2017; USFWS, unpublished data), nearing the published incipient lethal temperature of 20.9 °C for bull trout (Selong et al. 2001). Our data suggest that The Narrows became a thermal barrier for bull trout in July or early August, with the epilimnion gradually shrinking into the fall, but not breaking stratification

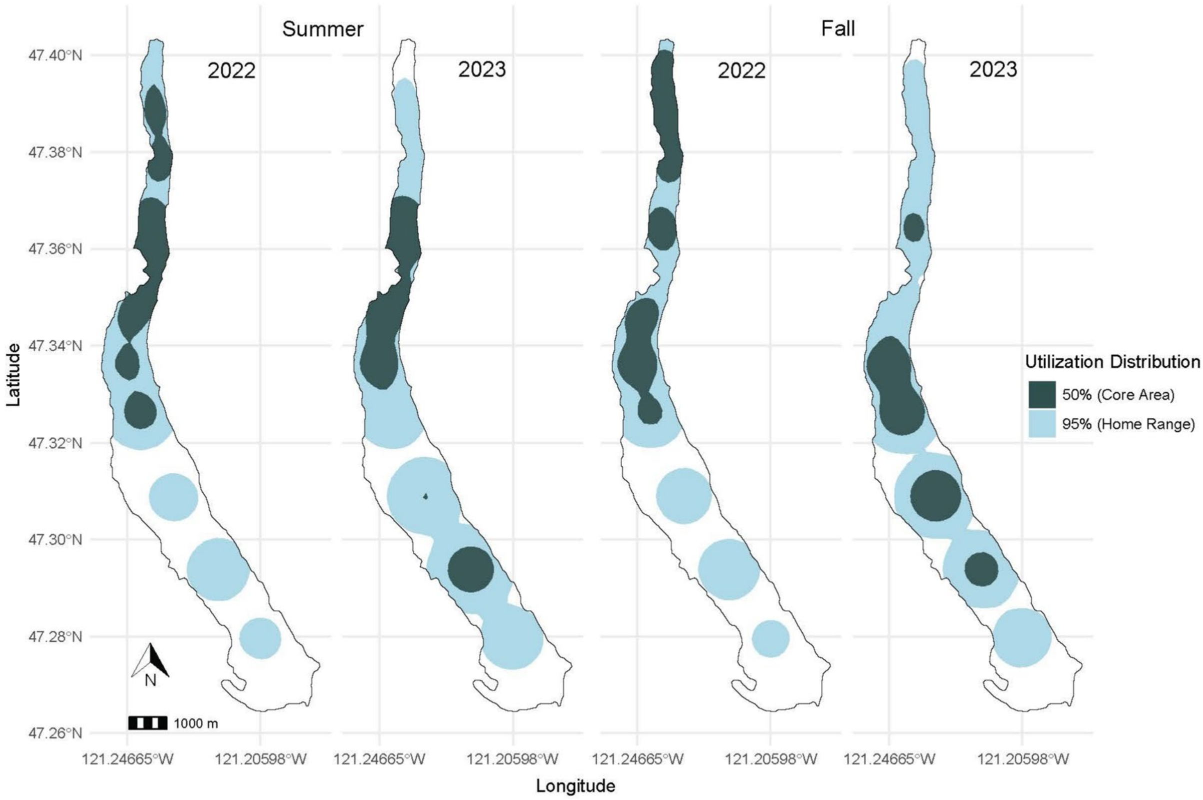

Fig. 5 Summer and Fall kernel utilization distributions by year for juvenile bull trout in Kachess Reservoir

before the physical barrier formed on October 8 when WSE dropped below 672 m. During this period in 2023, 86% of the remaining tagged fish were in Big Kachess, compared to 47% in 2022 (Fig. 6). This may indicate that Big Kachess offers more or higher quality habitat, particularly under drought conditions, considering all fish were originally released into Little Kachess and would have traveled to Big Kachess of their own volition. Importantly, the two spawning tributaries for bull trout in the system both drain into Little Kachess, so any fish remaining in Big Kachess past July in a drought year may face the decision of enduring the physiological stress associated with crossing The Narrows in shallow, warm water, or foregoing spawning.

Our model indicated that diel period was the strongest variable in predicting bull trout depth. Tagged bull trout underwent diel vertical migrations (DVM), using shallower habitat at night, which is consistent with observations in other systems (Gutowsky et al. 2013). However, this pattern varied by season, with strong DVMs in the winter and spring, while median day and night depths in summer both exceeded 10 m and varied by only 1.4 m (Fig. 4), likely because of stratification. Hansen

Table 3 Kachess Narrows crossings by tagged bull trout by season in 2022 and 2023. The Narrows forms at 678 m WSE and volitional fish passage ceases at 672 m WSE. The last crossing of The Narrows by a tagged bull trout in 2023 occurred at 683 m WSE in July

Year	Season	Narrows crossings	Minimum WSE (m)
2022	Winter	15	684.0
	Spring	11	687.9
	Summer	72	681.8
	Fall	36	679.4
2023	Winter	17	681.2
	Spring	51	682.8
	Summer	16 (all in July)	672.7
	Fall	0	670.6

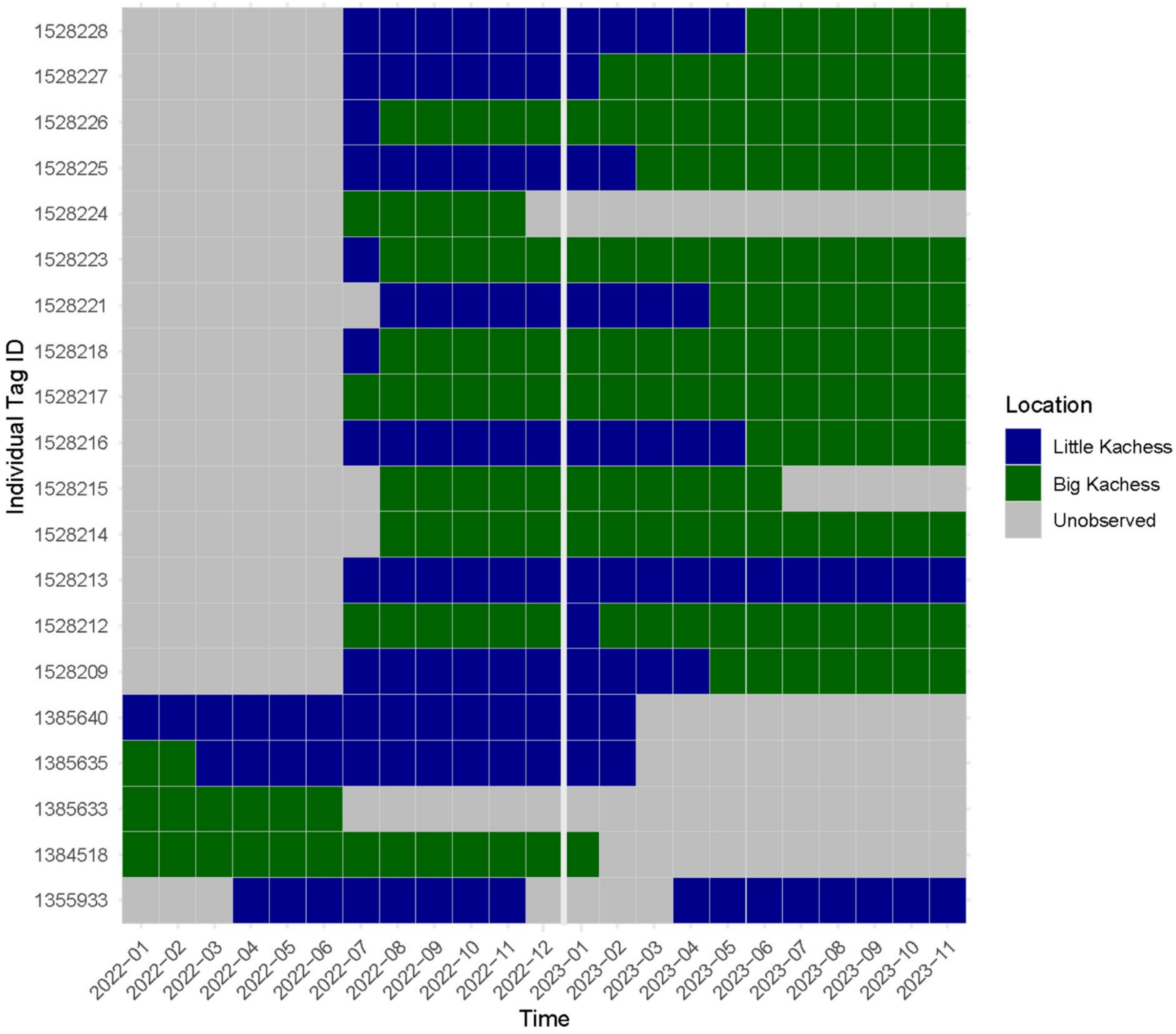

Fig. 6 Location of individual bull trout at the end of each month throughout the study, serving as a lower temporal resolution visualization of Narrows crossings. The thick white vertical line separates 2022 on the left from 2023 on the right. While tagged fish were distributed evenly between Little and Big Kachess in 2022, a shift in distribution is indicated by the transition to green tiles (presence in Big Kachess) in early to mid-2023

et al. (2017) documented similar DVM behavior in Kachess Reservoir by kokanee [*Oncorhynchus nerka* (Walbaum, 1792)], which are the main food source for bull trout in the system and are stocked biannually (Hansen et al. 2021). While DVMs in salmonids can be attributed to interactions between various abiotic and biotic drivers, and their intensity may vary on a spatiotemporal scale (i.e., Steinhart and Wurtsbaugh 1999; Scheuerell and Schindler 2003), it is likely that feeding behavior plays a substantial role for bull trout (Gutowsky et al. 2013). Additionally, our model

Table 4 Bayesian model outputs showing the predicted direction and amount of change in bull trout depth

Predictor	Directional change in depth	Depth change (m)
Diel period (day to night)	Decrease	3.13
1 °C temperature increase	Increase	0.24
1 m WSE increase	Increase	0.67

showed that variation among individual fish was a stronger predictor of depth distribution than temperature or WSE. Bull trout depth distribution reflected strong individuality and high activity, as has been documented in other systems (Gutowsky et al. 2013, 2016; Mochnacz et al. 2024) and species (Mehner and Kasprzak 2011). For example, one fish exhibited consistent use of deep areas in the lake, averaging 64 m in 2022 with regular dives up to 120 m. Conversely, another averaged 6 m in depth with maximum depths around 50 m in 2022. This individuality was also reflected in the kernel utilization distributions: individual core areas (50% UDs) ranged from 0.74 to 5.23 km^2, and home ranges (95% UDs) ranged from 2.52 to 15.60 km^2. The high level of individuality in bull trout likely reduces the proportion of variance in depth distribution that can be explained by our model's fixed effects. In this context, our r^2 of 0.39 may still indicate ecological significance of the model, while highlighting that modeled abiotic factors may not be sufficient in explaining bull trout depth distribution. Other potential predictors like biotic parameters (e.g., prey distribution and behavior), lake bathymetry, and flow (tributary inflow, dam discharge, etc.) may help explain additional variation in depth distribution unaccounted for by our model.

Changes in climate and increased stress on water resources are expected to manifest as range constrictions and population decreases in cold-water fishes (Gallagher et al. 2022). While streamflow in the snowpack- and glacier-fed headwaters of the YRB historically maintained through the summer from slow melt of the snowpack, climate models predict a 47–57% decrease in snow water equivalent by the 2040 s due to warmer winters resulting in more precipitation falling as rain (Elsner et al. 2010; Wagner et al. 2021). Climate projections and recent droughts have led to project proposals that increase active water storage in the YRB, which in Kachess Reservoir, may negatively impact trophic dynamics (Hansen et al. 2017). Our results indicate that a change in water management of Kachess Reservoir resulting in an increased drawdown of an additional 25 m WSE could have drastic impacts on the Kachess River and Box Canyon Creek bull trout populations. Under these conditions, thermal and physical barriers to passage across The Narrows would intensify and the period during which The Narrows are impassable would lengthen, isolating bull trout from their natal spawning streams in Little Kachess. Considering both populations that use Kachess Reservoir are critically depressed (WDFW 2004), further constraints on the number of fish available to contribute to the gene pool could have severe consequences for the future viability of these populations.

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Author contributions BRH: data acquisition, formal analysis, investigation, writing—original draft preparation, review, and editing. CDC: methodology, data acquisition, draft review, and editing. BAB: methodology, data acquisition, draft review, and editing. CAH: methodology, data acquisition, draft review, and editing. JGR: conceptualization, methodology, data acquisition, formal analysis, investigation, draft review, and editing.

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Data availability Data will be made available upon reasonable request.

Declarations

Competing interests The authors declare no competing interests.

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