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An Updated Assessment of Thermal Stress Thresholds in the Big Hole River, Montana: Thermal Exceedance Observations, Modeling and Trends

1.0 Introduction

The Big Hole river supports one of the last naturally-reproducing populations of fluvial Arctic grayling (*Thymallus arcticus*) in the coterminous United States (Vatland, 2015). As such, the Big Hole River has been the focus of many hydrologic and ecological studies, particularly related to cold-water habitat and the persistence of Arctic grayling (USFWS, 2020). Recent analyses, technical reports, and regulatory determinations have emphasized the biological relevance of thermal stress thresholds in this system, with 21 °C commonly cited as a chronic stress benchmark and 25 °C as an acute upper lethal threshold (Vatland, 2015). These thresholds have served as the basis for evaluating habitat suitability and population risk, including the U.S. Fish & Wildlife Service's 2020 "not warranted" listing determination (USFWS, 2020).

The U.S. Fish & Wildlife Service's 2020 Not Warranted determination (hereafter "2020 Determination" or "Determination") recognized rising air temperatures and altered flows as ongoing threats to Arctic grayling but concluded that conservation actions, particularly those under the Big Hole Candidate Conservation Agreement with Assurances (CCAA), had mitigated these risks sufficiently to maintain population resilience. While thermal stress events above 21 °C were documented, empirical monitoring suggested reduced durations of thermal stress events by 2017 (see 2020 Determination, Figure 4, available in the Supplementary Information as reference), consistent with the Service's interpretation of benefits from CCAA actions. This decline was attributed primarily to conservation actions such as flow augmentation and riparian restoration, that increased instream flows, reduced channel width-to-depth ratios, and improved shading. Although climate change was recognized as an ongoing stressor, its impacts were considered to be progressing more slowly than projected and at least partially offset by local habitat improvements. On this basis, the agency concluded that listing was not warranted at that time.

The analysis conducted here is designed to 1) reproduce and expand upon the core scientific elements of the 2020 Determination using updated datasets through 2025, applying fully transparent and reproducible methods, and 2) assess whether stream thermal regimes have changed meaningfully in the intervening years. Importantly, the Service's thermal exceedance analysis ended in 2017, leaving the last seven full years unexamined. A central focus of the present work is therefore to evaluate whether patterns observed up to 2017 (e.g. declining exceedance hours) have continued, stabilized, or reversed in the subsequent period. In doing so, we not only revisit the thermal exceedance trajectories emphasized in the 2020 Determination, but also quantify the drivers of daily stream temperature exceedance (>21 °C), assess long-term climate (air temperature) and hydrologic (streamflow) trends, and evaluate their joint influence on annual cumulative exceedance risk. This framing allows us to assess whether observed exceedance patterns are consistent with broader climatic drivers, or whether conservation actions provide buffering beyond what climate and flow alone would predict.

This reassessment is particularly timely given the Service's forthcoming Species Status Assessment (SSA) in 2026, which will again evaluate the persistence of Arctic grayling under the Endangered Species Act. By extending analyses beyond 2017 and incorporating updated records through 2025, the present work provides a transparent, reproducible basis for determining whether conservation measures continue to offset warming pressures, or whether recent climatic trends have altered the balance of thermal risk in the Big Hole River.

2.0 Methods:

2.1 Stream Temperature and Streamflow Data Assembly

We compiled hourly and/or sub-hourly stream temperature and discharge records for the Big Hole River by integrating U.S. Geological Survey (USGS) National Water Information System (NWIS) data with supplemental records from the State of Montana Stream Gaging Stations (StAGE) dataset. Candidate USGS sites were identified using NWIS metadata queries for sites with stream temperature and streamflow data, restricted to Montana. Site metadata were converted to a geospatial dataset and spatially intersected with the Hydrologic Unit Code 8 Big Hole watershed polygon (HUC8 10020004) to isolate relevant gages. StAGE site metadata were imported separately, converted to geospatial format, and harmonized with USGS metadata by standardizing site identifiers and station names. The two metadata sources were merged to yield a unified set of monitoring locations (n = 12; Figure 1).

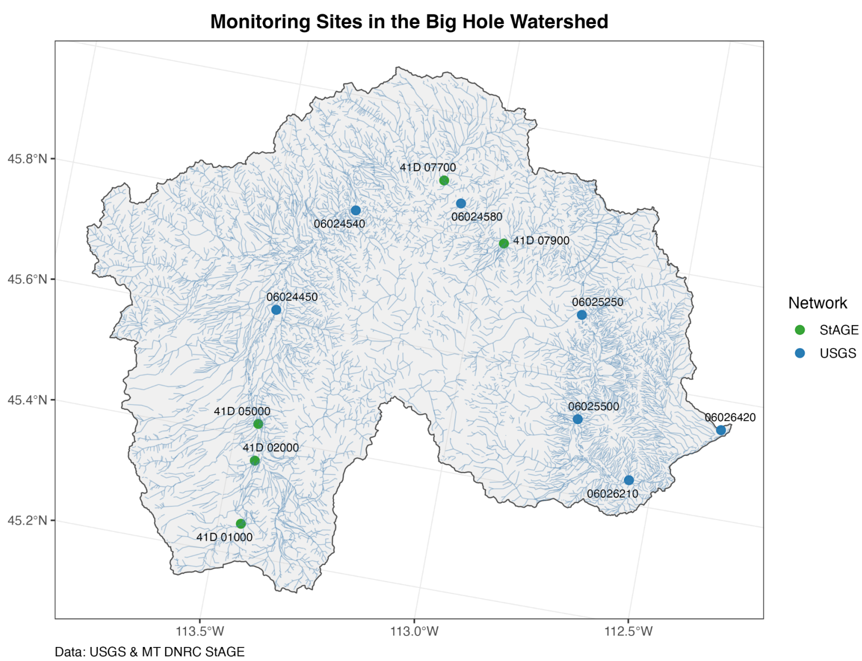

Figure 1: Site map showing the site locations used for the analysis.

Once candidate sites were identified, hourly (or sub-hourly) temperature and discharge records were then obtained from two sources: (i) USGS data was retrieved using the NWIS web service for parameters 00010 (temperature, °C) and 00060 (discharge, CFS), queried for the full available period of record through date of analysis (8/21/2025), and (ii) raw StAGE CSV files containing continuous temperature and discharge (downloaded from https://gis.dnrc.mt.gov/apps/stage/gage-report/). Both USGS NWIS and StAGE records were merged into a single dataset to facilitate a cohesive analysis. Because mainstem hydrographs reflect the realized sum of natural processes and managed inputs and removals (e.g., claimed CCAA augmentation, irrigation withdrawals, etc), attribution of temperature responses to any single component is not identifiable from gauge records. We therefore define ‘flow effects’ as the effect of total discharge on exceedance metrics and analyze discharge trends separately to interpret the combined management–climate signal.

2.2 Computation of Exceedance Hours per Year

Sub-hourly records were summarized by site, date, and hour, yielding a dataset of maximum hourly stream temperature and median hourly discharge. To focus on the biologically relevant summer season, we restricted records to May–October for each year present. Completeness of each site-year was assessed against expected hourly records: ≥80% of possible hourly observations between May 1 and October 31 had to be present to be used to compute annual exceedance hours. Site-years failing this threshold were excluded for this portion of the analysis, as annual exceedance hours cannot be accurately computed under substantial missingness. This threshold was used to balance inclusion of as many site-years as possible, while maintaining confidence in the associated results. For valid site-years, we computed two seasonal exceedance metrics: (i) the cumulative number of hours with maximum hourly stream temperature ≥21 °C, and (ii) cumulative hours ≥25 °C. These thresholds represent biologically relevant stress points for cold-water fish species such as Arctic Grayling: 21 °C is widely used to indicate chronic stress, while 25 °C is an acute threshold associated with severe stress and potential mortality. While both are important, we focus on the ≥21 °C threshold for the majority of the subsequent analysis. Annual exceedance summaries were joined with station metadata to produce site-specific time series. In total, four sites had enough information to be included in this analysis portion of the analysis.

For visualization (Figures 2 & 3), we plotted annual cumulative hours above each threshold by station. Individual annual exceedance values were displayed as points, while site-specific smoothed trends were estimated with generalized additive models (quasipoisson log-link), ensuring non-negative fitted values and robust standard errors. Smoothed trajectories were overlaid with 95% confidence bands, and facets were scaled independently to capture variation across sites. This workflow assumes the ≥80% completeness criterion adequately represents site-year exceedance dynamics. Together, these steps provide a reproducible, cross-network assessment of seasonal stream temperature exceedances in the Big Hole River watershed.

2.3 Daily Stream Temperature Exceedance Model — Generalized Linear Mixed Model (GLMM) for Exceedance Probability

To quantify the drivers of the annual exceedance values identified in Figure 2, we modeled the probability that daily maximum stream temperature exceeded 21 °C using a generalized linear mixed model (GLMM) framework. The response was binary (daily exceedance vs. non-exceedance of 21 °C) with a binomial error distribution and logit link (appropriate for binary probability modelling). Daily maximum and minimum air temperature (°C) and daily median streamflow (CFS) were included as covariates, each entered as linear terms on the log-odds scale. Daily maximum and minimum air temperature were extracted from the gridMET dataset (Abatzoglou et al., 2013) at the location of the gage site and streamflow was accessed via USGS and StAGE (computed from hourly discharge data described above). Finally, a categorical factor distinguishing pre- vs. post-2017 periods was included to test for a structural shift after 2017. The 2017 breakpoint was selected not arbitrarily, but because it represents both the end of the analysis period of the 2020 Determination and a phase when claimed improvements attributed to CCAA actions had already been observed (2020 Determination). This framing allows the post-2017 period to be evaluated in terms of whether those claimed beneficial effects have persisted, strengthened, or diminished, and whether exceedance sensitivity to air temperature and flow has shifted in a way that might indicate additional buffering attributable to CCAA actions. Because streamflow augmentation is a core component of the CCAA, and total instream flow is modeled explicitly as a covariate in this analysis, the breakpoint test should be interpreted as evaluating whether any additional buffering effect persists in the main stem Big Hole beyond what can be explained directly by air temperature and flow (e.g. tributary restoration, shading, etc).

To account for site-to-site heterogeneity, we specified random intercepts for each monitoring site and random slopes for daily maximum air temperature, allowing both baseline exceedance risk and thermal sensitivity to vary among sites. This specification reflects the expectation that sites could differ in their thermal response: shallow, unshaded reaches may have a warmer baseline temperature and respond more directly to hot air temperatures, while deeper or groundwater-fed sites may be generally cooler and more buffered. Because daily exceedances exhibit serial correlation (e.g., if stream temperature is warm today, it is more likely to be warm tomorrow as well), we incorporated an autoregressive [AR(1)] correlation structure on residuals, with ρ estimated from the lag-1 autocorrelation of Pearson residuals. The AR(1) structure assumes residuals on day *t* are correlated with those on day *t–1*, with correlation decaying at longer lags. This adjustment does not alter point estimates but provides more realistic standard errors and confidence intervals. Models were fit using restricted maximum likelihood with a discrete approximation for computational efficiency.

To evaluate robustness, we fit two versions of the exceedance probability model. The first model included all available daily site records, maximizing sample size (n = 16,242 daily records computed from 399,677 hourly records). However, because not all gages spanned both before and after 2017, we also fit a “symmetric” model restricted to sites with relatively complete records from May - October (using the 80% threshold described above) with valid data on both sides of the 2017 breakpoint (n = 8,724 daily records). Although, "symmetric" should not be interpreted as an even number of observations on either side of the 2017 breakpoint, simply that there was at least a year of valid seasonal data on either side. This balanced subset ensured that period effects were evaluated under as comparable temporal coverage as possible. Both models retained the same GLMM structure (binomial logit, site random intercepts, site-specific maximum air temperature slopes, AR(1) residual correlation), allowing direct comparison of fixed effects across the two datasets.

Our modeling approach assumes: (i) the logit-linear form adequately describes the effects of air temperature and streamflow on exceedance probability; (ii) the AR(1) structure adequately captures temporal dependence within each site's daily series; (iii) missing days represent independent breaks that reset the correlation; and (iv) exceedance outcomes are conditionally independent given the predictors and correlation structure.

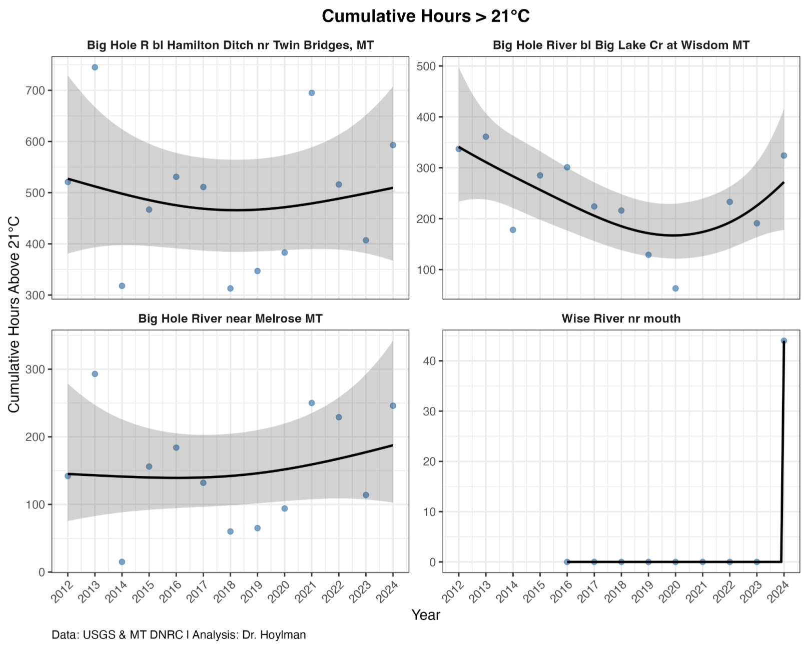

Figure 2: Annual exceedance hours for the 21 °C threshold across all sites.

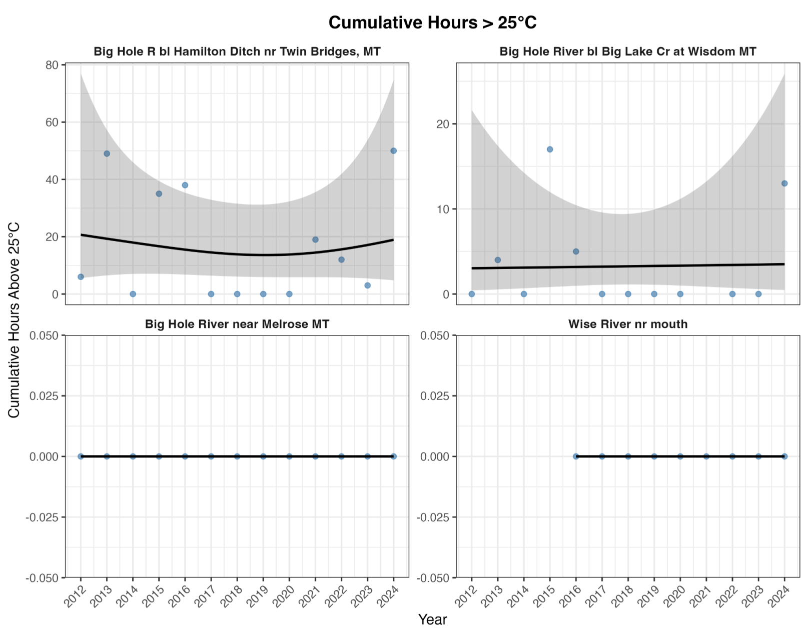

Figure 3: Annual exceedance hours for the 25 °C threshold across all sites.

2.4 Seasonal Air Temperature Trends

To place exceedance dynamics in the context of long-term climate change, we quantified trends in warm-season air temperature across the Big Hole watershed. Daily maximum air temperature records from the gridMET dataset (Abatzoglou 2013) were extracted at each monitoring site for 1979–2024 and restricted to May–October, the period of biological relevance for Arctic grayling. Annual medians of daily maximum temperature were calculated by site and year. To estimate long-term warming rates, we fit a linear regression model with site fixed effects, using year as the predictor and seasonal median temperature as the response. The slope on year from this model represents the shared basin-wide warming rate (pooled effect, °C per decade), which reflects the common temporal trend across all sites after accounting for baseline differences among gages. Site-specific slopes were also estimated separately to assess whether local warming trends were significant ($p < 0.05$). This framework captures the basin-wide warming signal while allowing detection of spatial heterogeneity in magnitude.

2.5 Streamflow Trends

In parallel, we assessed long-term changes in streamflow (~1994-2024), to evaluate whether hydrologic conditions have shifted in ways that might interact with warming temperatures and to capture any relevant trends associated with mainstem CCAA management actions (e.g., streamflow augmentation). Daily median discharge records from USGS gages were summarized to May–October medians for each site and year through 2024. To estimate decadal-scale changes, we fit a linear regression model with site fixed effects, using year as the predictor and seasonal median discharge as the response. The slope on year from this model represents the shared basin-wide flow trend (pooled effect, CFS per decade), which reflects the common temporal signal across all sites after controlling for site-level baseline differences. Site-level regressions were also fit independently, with significance tests ($p < 0.05$) used to evaluate whether individual gages exhibited detectable local trends. This dual approach identifies whether there is a consistent basin-wide directional signal, while also resolving site-to-site variability in hydrologic responses. We restricted this analysis to USGS gages because they provide much longer and more continuous records than StAGE, allowing robust detection of decadal-scale trends.

2.6 Joint Air Temperature–Streamflow Controls on Exceedance

Finally, we explicitly quantified how cumulative warm-season exceedance hours respond to interannual variability in both air temperature and streamflow (May - October in all cases). Seasonal exceedance hours (≥21 °C) were joined with site-year medians of daily maximum air temperature and daily median discharge. A multiple linear regression model was fit with exceedance hours as the response and air temperature and streamflow as predictors, with site fixed effects included to account for baseline differences among gages. This design allowed us to estimate the marginal effect of each driver while holding the other constant, effectively providing partial effects for air temperature (hours gained per +1 °C) and for flow (hours reduced per +100 CFS). Together, these analyses link long-term climate warming (section 2.4) and hydrologic trends (section 2.5) to their expression in seasonal cumulative thermal exceedance risk.

3.0 Results:

3.1 Seasonal Exceedance Hours

Hourly records from USGS and StAGE gages showed strong interannual variability in cumulative seasonal hours above biologically relevant thresholds (21 °C, Figure 2 and 25 °C, Figure 3). Across sites, hours ≥21 °C ranged from <50 (Wise River, near mouth) to >700 (Big Hole River below Hamilton Ditch near Twin Bridges, MT) in individual years (Figure 2). In contrast, hours ≥25 °C were rare, generally <60 per season, and often absent at several sites (Figure 3). Generalized additive models (GAMs) highlight non-linear temporal patterns, with some sites showing declining exceedances during the mid-2010s followed by increases after 2020 (albeit with large confidence intervals). There was considerable variability across sites and years. The strongest pattern appears at the Big Hole River below Big Lake Creek near Wisdom, MT (Figure 2) where increases in exceedance hours were observed following 2020. The extreme downstream site (Hamilton Ditch) consistently exhibited the longest periods above both thresholds, whereas the Wise River site only exceeded 21 °C in the most recent year (2024).

3.2 Exceedance Probability Models

Generalized linear mixed models (GLMMs, Tables 1,2) confirmed that daily exceedance risk (risk of stream temperature exceeding 21 °C) was strongly governed by both air temperature and streamflow. In the all-data model, each +100 CFS increase in daily median streamflow reduced the odds of exceeding 21 °C by ~16% ($p < 0.001$), while +1 °C increases in daily maximum and minimum air temperature raised exceedance odds by ~26% and ~22%, respectively (both $p < 0.001$). The pre- vs post-2017 effect was not significant ($p = 0.235$). Site-specific random effects were also not significant, indicating broadly consistent exceedance sensitivity across monitoring sites. The AR(1) residual structure accounted for daily temporal autocorrelation, and the model explained ~59.9% of deviance. The marginal effect of daily maximum air temperature on exceedance probability (>21 °C) per site shows the expected probability of exceedance as air temperature increases, holding streamflow and minimum temperature at site medians (Figure 4). The steep rise above ~20–25 °C highlights the dominant role of air temperature in driving thermal stress, with site-to-site variation reflecting covariate baselines rather than heterogeneous slopes.

Table 1: Fixed-effects results from the exceedance probability model (AR(1) GLMM) using all data.

Exceedance Model (AR(1) GLMM): Fixed Effects

Outcome: Pr(stream daily max > 21 °C)

Predictor	Log-odds	SE	z	p	Odds ratio	95% CI
Intercept	-8.352	0.526	-15.875	<0.001	0.00	[0.00, 0.00]
Streamflow (per +1 CFS)	-0.002	0.000	-13.479	<0.001	1.00	[1.00, 1.00]
Max Air Temperature (per +1 °C)	0.229	0.018	12.889	<0.001	1.26	[1.21, 1.30]
Min Air Temperature (per +1 °C)	0.205	0.014	14.697	<0.001	1.23	[1.19, 1.26]
Period: pre-2017 vs post-2017	0.129	0.109	1.188	0.235	1.14	[0.92, 1.41]

Interpretation. Exceedance risk (> 21 °C) was strongly governed by air temperature and streamflow. Each +100 CFS increase in discharge lowered the odds by ~16% ($p < 0.001$), while a +1 °C increase in maximum and minimum air temperature raised the odds by ~26% and ~23%, respectively (max $p < 0.001$; min $p < 0.001$). The pre-2017 vs post-2017 period effect was not significant (OR ≈ 1.14; p 0.23). Random effects were not significant, suggesting broadly consistent baseline risk and thermal sensitivity across sites. An AR(1) residual structure accounted for temporal clustering. Overall, the model explained ~59.9% of deviance (adj. $R^2 \approx 0.6$).

In the "symmetric" model, restricted to sites with pre- and post-2017 records, results were similar. Each +100 CFS increase in streamflow reduced exceedance odds by ~18% ($p < 0.001$), while +1 °C increases in maximum and minimum air temperature raised exceedance odds by ~25% and ~29%, respectively (both $p < 0.001$). Again, the pre- vs post-2017 effect was not significant ($p = 0.211$). Random effects remained non-significant, suggesting no evidence for heterogeneous site-level departures from the fixed effects. This filtered model explained ~61% of deviance.

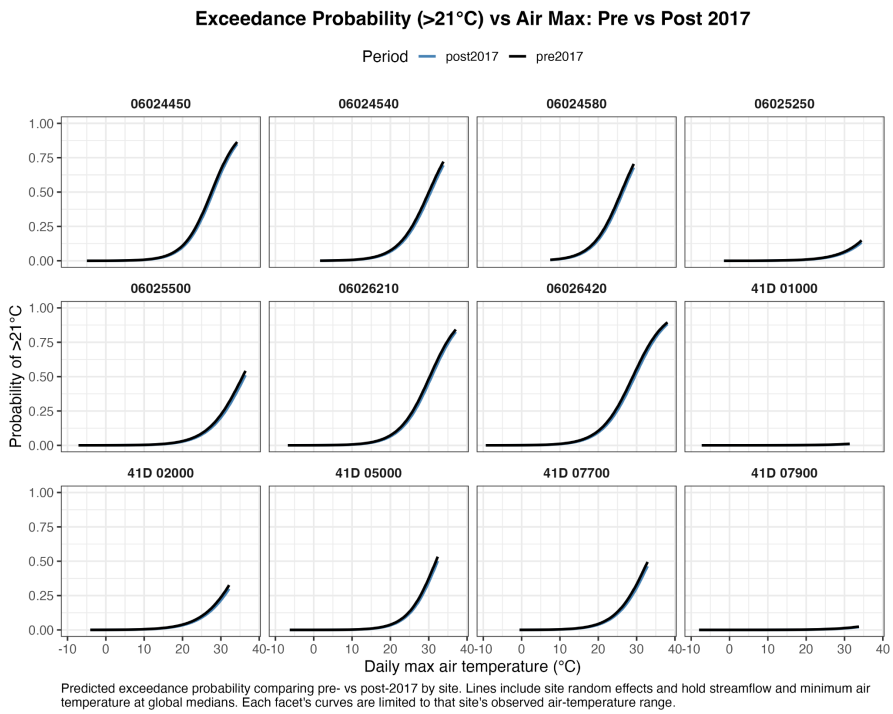

Figure 4: Predicted probability that daily maximum stream temperature exceeds 21 °C across Big Hole sites. Curves show the modeled influence of maximum air temperature, with other factors held at site-specific medians. The pre- and post-2017 effects are not statistically significant, but shown for reference.

Table 2: Fixed-effects results from the exceedance probability model (AR(1) GLMM) using the "symmetric" dataset.

Exceedance Model (AR(1) GLMM): Fixed Effects

Outcome: Pr(stream daily max > 21 °C)

Predictor	Log-odds	SE	z	p	Odds ratio	95% CI
Intercept	-8.464	0.382	-22.141	<0.001	0.00	[0.00, 0.00]
Streamflow (per +1 CFS)	-0.002	0.000	-12.473	<0.001	1.00	[1.00, 1.00]
Max Air Temperature (per +1 °C)	0.224	0.044	5.051	<0.001	1.25	[1.15, 1.36]
Min Air Temperature (per +1 °C)	0.252	0.019	13.470	<0.001	1.29	[1.24, 1.34]
Period: pre-2017 vs post-2017	0.148	0.119	1.251	0.211	1.16	[0.92, 1.46]

Interpretation. Exceedance risk (> 21 °C) was strongly governed by air temperature and streamflow. Each +100 CFS increase in discharge lowered the odds by ~18% ($p < 0.001$), while a +1 °C increase in maximum and minimum air temperature raised the odds by ~25% and ~29%, respectively (max $p < 0.001$; min $p < 0.001$). The pre-2017 vs post-2017 period effect was not significant (OR ≈ 1.16; p 0.21). Random effects were not significant, suggesting broadly consistent baseline risk and thermal sensitivity across sites. An AR(1) residual structure accounted for temporal clustering. Overall, the model explained ~61.1% of deviance (adj. $R^2 \approx 0.63$).

It is important to note that these effect sizes are expressed on the odds scale. For example, an odds ratio of 1.26 for maximum air temperature (table 1) means that each +1 °C increase multiplies the odds of exceedance by 1.26 (26%). These multiplicative effects compound: a +5 °C increase corresponds to $1.26^5 \approx 3.2$, or roughly a threefold increase in odds. However, the translation from odds to absolute probability depends on the baseline exceedance risk. For instance, when daily maximum air temperature was ~15 °C, predicted exceedance probability was generally very low (<1%); at ~20 °C, predicted probability increased modestly (~3%); and at ~25 °C, probability rose to ~8% (when considering the global fixed effects). Thus, while odds ratios convey relative changes consistently across the covariate range, their practical ecological meaning is best interpreted through predicted probabilities spanning the observed temperature distribution.

3.3 Seasonal Air Temperature Trends

Warm-season air temperatures in the Big Hole watershed have increased significantly over the past four decades. Across all sites, pooled May–October median daily maximum temperatures rose at a rate of 0.42 °C per decade (95% CI: 0.34–0.49). Site-level regressions indicate that this warming signal is broadly consistent across the watershed, with several gages showing individually significant positive trends ($p < 0.05$). While baseline temperatures differ among sites, the directional trend is uniform, underscoring a watershed-wide climatic warming trajectory that provides important context for interpreting stream thermal exceedance patterns.

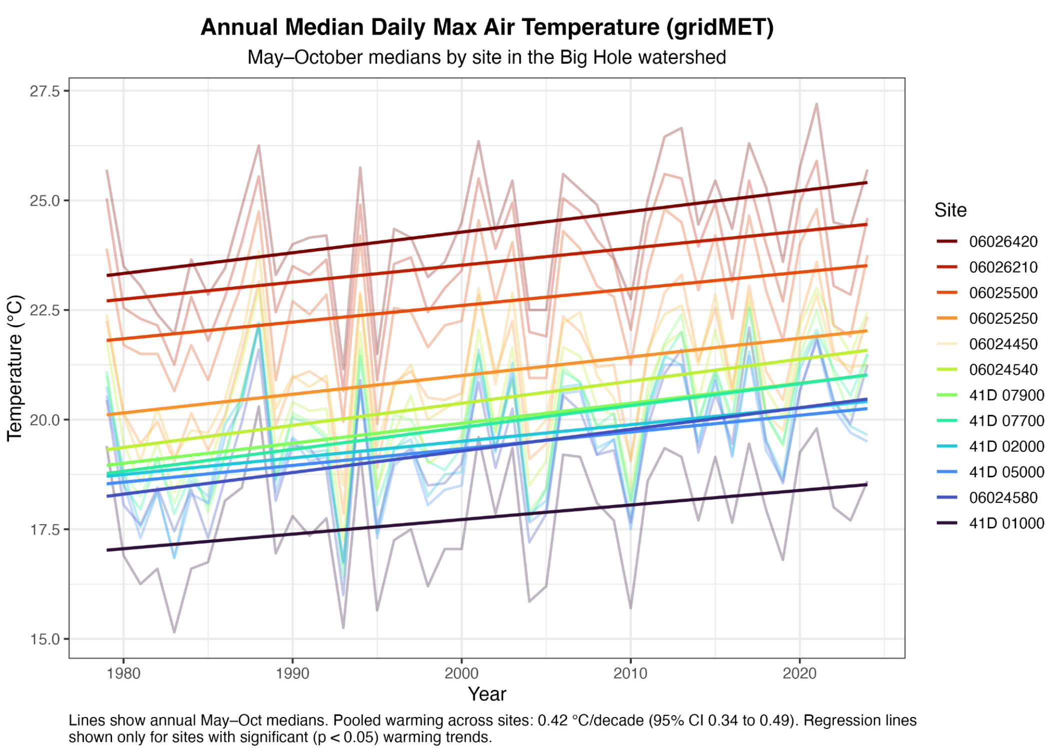

Figure 5: Long-term trends in May–October median daily maximum air temperature (gridMET, 1979–2024) across Big Hole River monitoring sites. Linear regression trend lines indicate locations with significant warming trends.

3.4 Streamflow Trends

Warm-season streamflows in the Big Hole River show evidence of site-specific flow stability or decline over the past decade. When considering all gages together, the pooled May–October median discharge decreased at a rate of −49.4 CFS per decade (95% CI: −91 to −7.8, $p < 0.05$). While only one site (06024450; Big Hole River bl Big Lake Cr at Wisdom MT) exhibited a statistically significant site-specific negative trend ($p < 0.05$), this site represents flow in the upper reaches of the main stem Big Hole. This pattern suggests that, despite interannual variability, trends indicate declining summer streamflow.

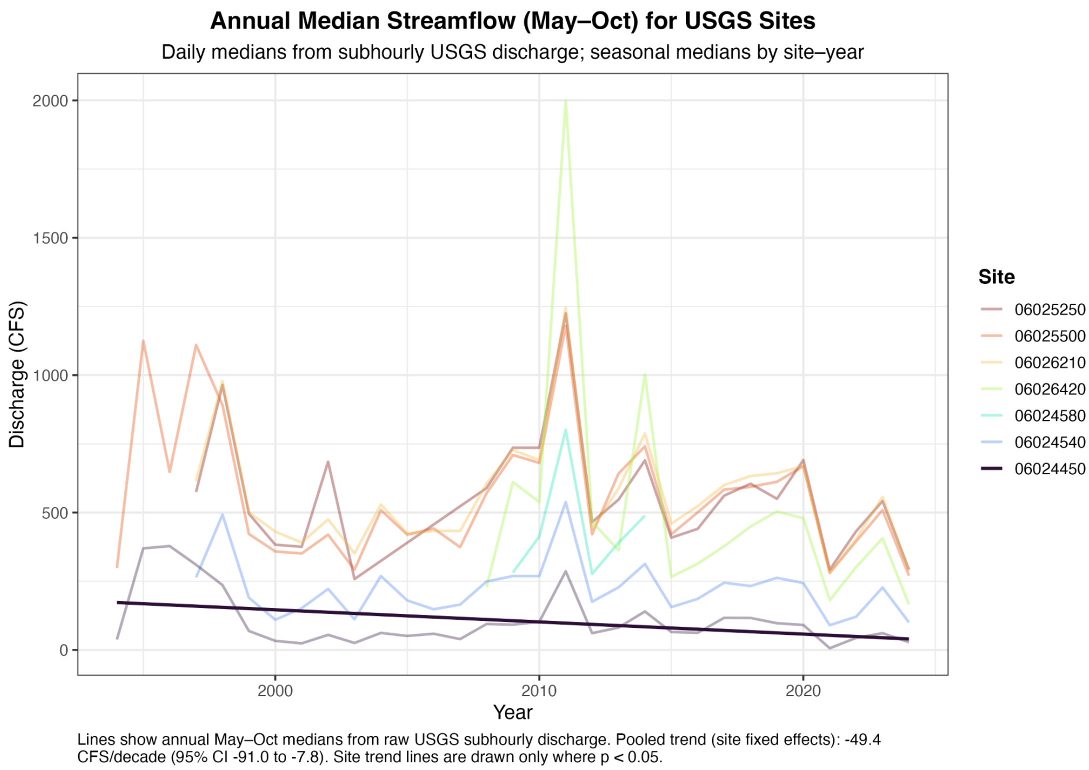

Figure 6: Long-term trends in May–October median streamflow (USGS gages) across Big Hole River monitoring sites. Linear regression trend lines indicate stations with significant ($p < 0.05$) declines.

3.5 Joint Air Temperature–Streamflow Controls on Exceedance

Seasonal exceedance hours were positively associated with warm-season air temperature (Figure 7) and negatively associated with streamflow. Across sites and years and when holding flow constant, each +1 °C increase in median May–October daily maximum air temperature corresponded to ~87 additional hours ≥ 21 °C ($p < 0.001$). Holding temperature constant, each +100 CFS increase in median seasonal discharge corresponded to ~26 fewer hours ≥ 21 °C ($p = 0.001$). The model explained a substantial fraction of interannual variability (adj. $R^2 = 0.63$), indicating that exceedance dynamics can be parsimoniously described by these two predictors. It is important to note that the sites included in Figures 5–7 differ based on the availability of specific variables (air temperature, streamflow, or stream temperature) and the length of record required for trend analyses (e.g., long records were necessary for streamflow trends in Figure 6).

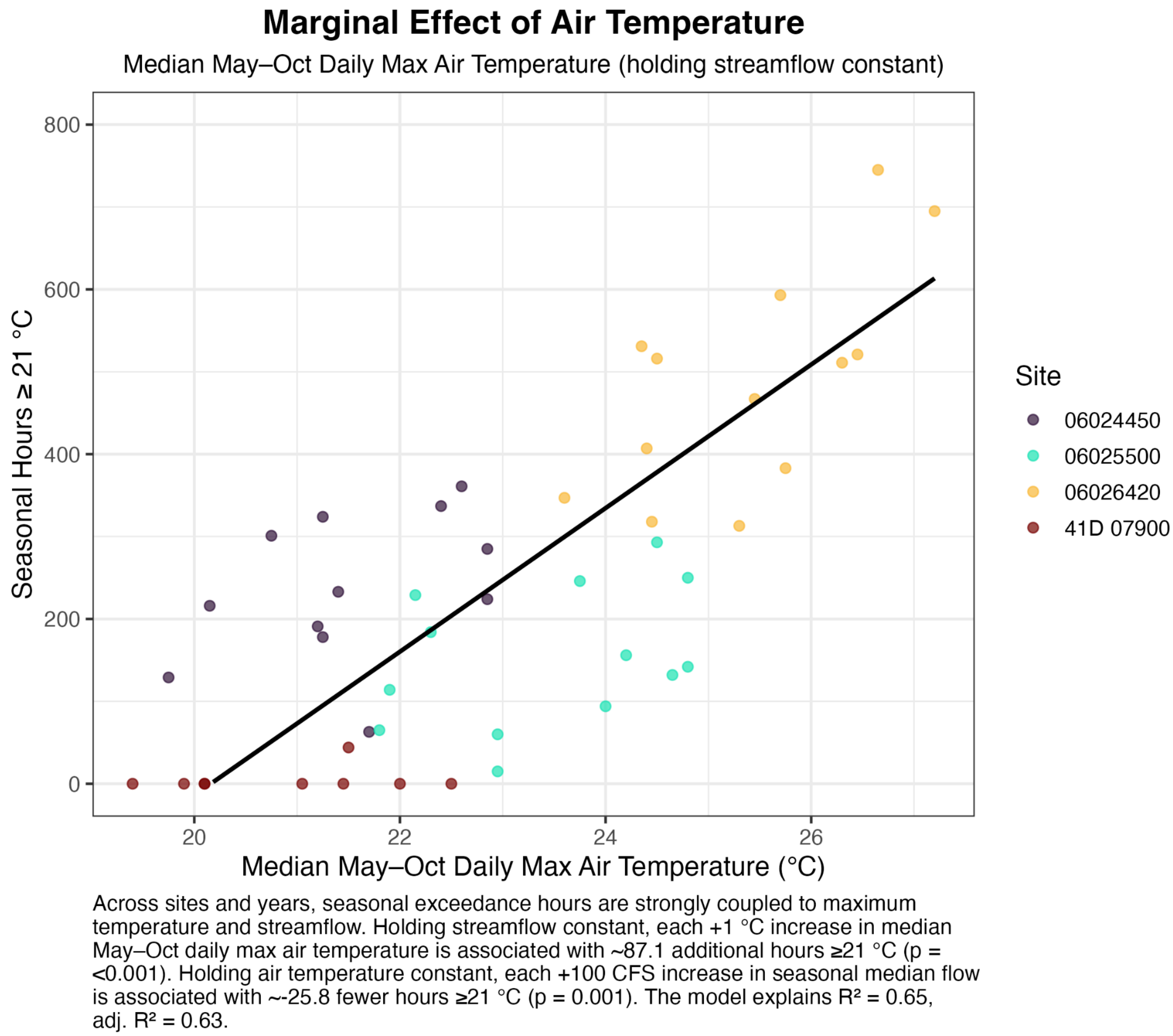

Figure 7: Marginal effect of air temperature on seasonal exceedance hours (≥21 °C) in the Big Hole River. Points show site-year values of median May–October daily maximum air temperature and seasonal exceedance hours. The fitted line represents the pooled regression relationship, holding streamflow constant. Model estimates indicate ~87 additional hours ≥21 °C per +1 °C increase in air temperature ($p < 0.001$); adjusted $R^2 = 0.63$.

4.0 Discussion:

This analysis integrates multiple lines of evidence to provide an updated picture of thermal risk for Arctic grayling in the main stem of the Big Hole River, extending the record beyond the analysis referenced in the U.S. Fish and Wildlife Service’s 2020 “not warranted” determination (up to ~2017). Exceedance observations showed strong interannual variability, with exceedance hours declining in some sites prior to 2017 but increasing again in recent years (Figures 2–3). Exceedance probability models confirmed that daily risk of >21 °C is consistently governed by both air temperature and streamflow, with no detectable change in sensitivity before versus after 2017 once covariates were controlled for (Figure 4, Tables 1,2). Long-term climate analyses demonstrated a clear warming trend of ~0.42 °C per decade since 1979 (Figure 5), while hydrologic analyses revealed declining summer flows at the watershed scale (pooled May–October median discharge shows statistically significant declines) with site level variability (Figure 6). Joint regressions linked these drivers to exceedance risk, showing that warmer seasons correlate with more exceedance hours while higher flows provide partial buffering (Figure 7). Taken together, these analyses demonstrate that exceedance dynamics in the Big Hole remain tightly coupled to regional climate forcing, with enhanced streamflow exerting a buffering influence when available. However, the capacity for flow to mitigate thermal risk is limited by observed declines in summer discharge representative of broader trends. Whereas the 2020 Determination reported a declining exceedance trajectory through 2017, our updated analyses show that the decline did not persist; moreover, after controlling for air temperature and total discharge, we find no statistical evidence of additional buffering in the post-2017 period.

The 2020 Determination concluded that cumulative exceedance hours declined through 2017 at both mainstem and tributary sites, a pattern attributed in part to conservation actions under the Big Hole Candidate Conservation Agreement with Assurances (CCAA). Our updated record shows that this decline did not persist beyond 2017 in the main stem Big Hole River (data from tributaries was not available): exceedance hours have fluctuated and, in some locations, increased in several recent summers (Figure 2), broadly paralleling warmer seasonal air temperature conditions and low flows. Importantly, neither the “all-data” nor the “symmetric” exceedance probability models (Table 1 & 2) detected a significant structural break in exceedance sensitivity before versus after 2017 once air temperature and streamflow were controlled for. This indicates that any claimed buffering effects of the CCAA beyond flow augmentation (e.g., riparian restoration, channel morphology, shading) have remained relatively consistent over time; there is no statistical evidence of increased buffering capacity in the post-2017 period that is not already accounted for in this analysis. In other words, observed changes in exceedance frequency since 2017 are primarily explained by climatic forcing and flow variability rather than a shift in the underlying system response.

Based on the pooled regression model (watershed scale) with site fixed effects, we estimate that each +1 °C increase in median May–October air temperature corresponds to ~87 additional seasonal exceedance hours ≥ 21 °C, while each +100 CFS increase in median streamflow reduces exceedance by ~26 hours. Given the observed long-term warming trend of +0.42 °C per decade (1979–2024), this translates to ~37 additional exceedance hours per decade, assuming consistent trends. Offsetting this increase would require approximately +140 CFS per decade in median seasonal flow. However, we find no evidence in the observed, long-term streamflow records that flows are increasing in ways that could compensate for future warming. In fact, we detected significant declining trends at the watershed scale suggesting this type of future offset is very unlikely. While sites differed in their absolute thermal baselines (some reaches are consistently warmer or cooler due to geomorphology, groundwater influence, or network position), once air temperature and streamflow are accounted for, our exceedance probability models show no statistical evidence of additional site-level differences in either baseline exceedance risk or sensitivity to air temperature. This indicates that while the absolute number of exceedance hours varies with local conditions, continued climate warming is expected to increase thermal risk across all sites in a broadly consistent way.

Flow augmentation has emerged as the most direct and effective management lever in the mainstem Big Hole River, consistent with the 2020 Determination’s emphasis on conservation flows. Although increased discharge clearly offsets some of the warming-driven rise in exceedance hours, long-term hydrologic trends do not support the expectation that such buffering will be available at the scale needed in the future (Figure 5 & 6). Although most individual sites did not show statistically significant trends in warm-season flows, the pooled regression across all gages indicates a significant basin-wide directional decrease of −49 CFS per decade (95% CI: −91 to −7.8, $p < 0.05$). This pooled approach integrates information across sites and years, increasing statistical power to detect a shared directional signal even where individual site records are noisy. This suggests that the buffering capacity of flow augmentation is fundamentally constrained: while increasing flow remains the most immediate lever, if historical patterns of stable-to-declining summer discharge persist, it cannot be expected to scale proportionally with rising temperatures. Because exceedance hours serve as direct proxies for sublethal stress and habitat contraction, continued reliance on flow augmentation alone risks leaving grayling populations in the main stem Big Hole river vulnerable if summers become warmer and drier as broadly projected (Whitlock et al., 2017).

Taken together, these results reinforce the conclusion that exceedance risk in the Big Hole River remains tightly coupled to air temperature and moderated by flow. While the CCAA has claimed to have provided measurable benefits through flow augmentation and habitat restoration, those claimed benefits have not led to a detectable change in exceedance sensitivity since 2017. Therefore, there is no statistical evidence of additional buffering in the main stem river from non-flow augmentation CCAA activities following the effects identified in the 2020 Determination. Ultimately, this means that while management can theoretically moderate risk, exceedance dynamics in the Big Hole should be expected to track regional climate forcing, underscoring that conservation actions taken thus far must be viewed as, at best, temporary buffers rather than durable solutions in the face of ongoing warming. These results also highlight the importance of recognizing climate non-stationarity: while exceedance sensitivity remains consistent, the shifting baseline of warmer air and declining flows will push exceedance risk steadily higher into the future.

Plain-language takeaway. Hotter summers and lower flows are the main reasons the Big Hole is warming. When air temperatures rise, the river warms; when flows are lower, the river is also warmer. Long-term records show summer air temperatures rising by ~0.42 °C per decade (statistically significant) and summer flows either stable or declining (a statistically significant –49 CFS per decade at the watershed scale). In some locations, exceedance hours that had declined before 2017 have increased again in recent summers, broadly tracking warmer air temperatures and low flows. Our analyses indicate that while higher flows can theoretically buffer thermal stress, in practice the observed flow trends do not provide this offset. Given these results and current climate trends, thermal risk to Arctic grayling is expected to increase significantly in the years ahead.

Supplemental Information, Data and Code Availability:
All data, code and supplementary information can be accessed at https://github.com/zhoylman/bighole-hydro.

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