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Research Article

Migration of Mongolian Grayling (*Thymallus brevirostris*) in the Khovd River, Mongolia: Implications for Ongoing Hydropower Development

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Mongolian grayling is a large piscivorous grayling endemic to the endorheic basin of the Khovd and Zavkhan River systems in western Mongolia. Ongoing large-scale hydropower development in the Khovd River has raised concerns about potential impacts on the Mongolian grayling populations in the area. Very little is known about the behavior and biology of Mongolian grayling, which makes it difficult to predict the impacts of damming and to plan for conservation and management mitigation actions. In this study, we used acoustic telemetry to track migration and survival of Mongolian grayling in the Khovd River system before the onset of hydropower construction. We found that the Mongolian grayling in the Khovd River conduct extensive seasonal migrations (> 170 km) to reach overwintering and spawning habitat and that migration routes pass through the Shijigtiin Canyon which is currently being developed for hydropower. We also found that Mongolian grayling in the downstream Khar Lake predominantly reside in the lake and only use lotic habitat during the spawning season, including the dammed Chono-Kharaikh River. Based on our results, we argue that the ongoing hydropower development of the Khovd River will have severe impacts on the grayling population by disrupting the annual migration cycle, prohibiting access to spawning and overwintering habitat, and altering flow regimes on downstream spawning grounds.

Keywords: acoustic telemetry; Altai; behavior; conservation; endemic; endorheic river

1. Introduction

Mongolian grayling (*Thymallus brevirostris,* Kessler 1879) is a thymallus subspecies endemic to the endorheic basin of the Khovd and Zavkhan river systems of the Altai–Sayan Mountains of western Mongolia [1]. It is a large bodied and fast growing fish that may weigh as much as 5 kg and reach more than 75 cm in length [2]. In contrast to other thymallus subspecies, the Mongolian grayling feature distinct morphological characteristics associated with a piscivore predatory lifestyle, such as pronounced teenths on jaws, vomer and tongue, a large mouth, and extensive articulation of the mandible [2]. It is a top predator in the species poor fish communities inhabiting the remote semiarid lakes and

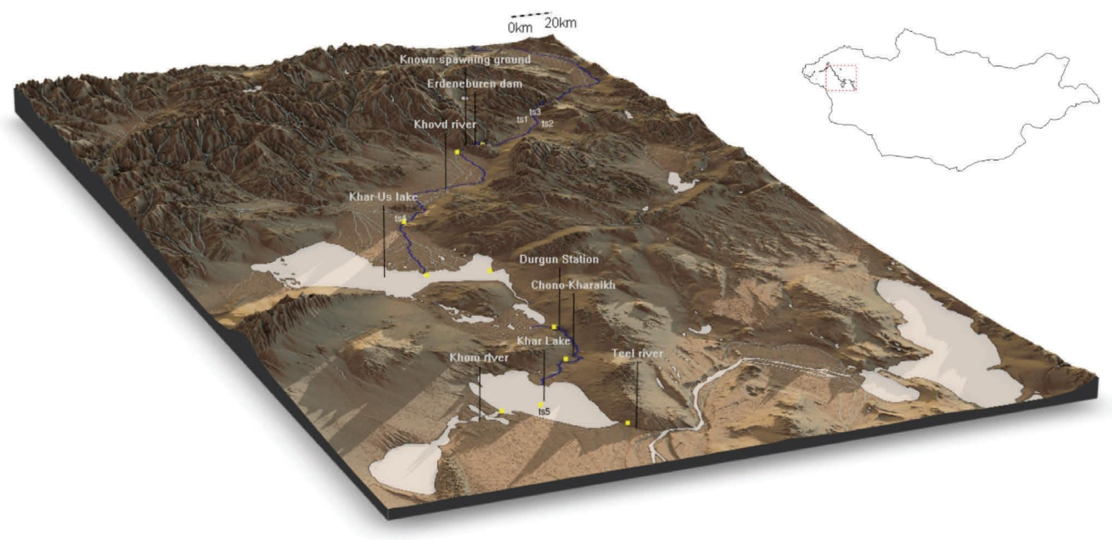

Figure 1: The study site. Positions of acoustic telemetry receivers are indicated by yellow squares. ts1–5 represent tagging sites. The figure was created using rayshader [11] and geographic data from the CGIAR-CSI GeoPortal and the Administration of Land Affairs, Geodesy, and Cartography of Mongolia (ALAGaC).

streams of western Mongolia, preying primarily on the endemic cyprinid Potanin's Altai Osman (*Oreoleuciscus potanini*) as well as cannibalizing on juvenile conspecifics [3]. Although some attention has recently been given to the evolutionary history and phylogenetics of the Mongolian grayling [1, 2, 4], very little is still known about its biology and behavior. Basic knowledge important for effective management and conservation, such as seasonal migration patterns and survival, is very limited, making it difficult to design effective management plans and understand the potential impact of anthropogenic threats.

The natural resources of western Mongolia are increasingly being explored by extraction industries such as mining and hydropower, which may have severe consequences for the endemic fish communities in the region [5]. Given the restricted distribution range of the Mongolian grayling, any anthropogenic activity that may degrade or limit access to critical environments such as spawning and overwintering habitat may pose a significant threat to the viability of the species. Mongolian grayling is currently one of the most threatened fish species in Mongolia, with habitat degradation and illegal fishing being primary threats [5–7], and the species is listed as "vulnerable" on the Mongolian Red list [8]. Extensive plans for large-scale hydropower development of the Khovd River, the main watershed of the Mongolian grayling, raise conservation concerns, and more information regarding the potential impact is urgently needed [9].

Many stream fishes use distinct habitats to fulfill different life-history functions—overwintering, feeding, and spawning—and migrate among them across seasons [10]. Maintaining connectivity between such habitat may hence be crucial for the life-cycle completion. In this study, we used acoustic telemetry to investigate the movements of Mongolian grayling (*T. brevirostris*) within the Khovd River system in western Mongolia, focusing on areas surrounding the planned Erdeneburen Hydropower Station on the Khovd River and the existing Durgun Hydropower Station on the Chono-Kharaikh River. The main objectives were to describe the seasonal migration dynamics and apparent survival of Mongolian grayling and evaluate how hydropower development may affect population connectivity and access to critical habitats.

2. Materials and Methods

2.1. Study Area. The Khovd River is a 516-km long unregulated river originating in the alpine lakes of the Mongolian Altai and empty into the Khar-Us Lake in the great-lake depression region (Figure 1, see Figure A1 in appendix for environmental characteristics of the study area). The watershed is 50,149 km^2, and the river has a mean annual discharge of 85 m/s^3 and falls over 900 m from the source to the mouth. It is partially glacial fed and may become large and silty during summer. The river system contains important habitat for fish and birds, including extensive floodplains and Ramsar wetlands (wetlands designated as internationally important under the Ramsar Convention on Wetlands). The Khar-Us Lake is a large (946 km^2) shallow (mean/max depth: 2.5/5 m) tectonic freshwater lake that is connected with the Khar Lake via the 37-km long Chono-Kharaikh River [12] (Figure 1). The Khar Lake (area: 574 $km^{2,}$ mean/max depth: 4.5/7 m) is a freshwater lake that connects to the Zavkhan River system via the Teel River in the west and to the saline Durgun Lake via the Khom River in the south [12]. The river and lake system contain a species poor endemic fish fauna primarily consisting of Mongolian Grayling, Potanin's Altai Osman (*O. potanini*), and the Siberian stone loach (*Barbatula toni*).

The Chono-Kharaikh River is dammed by the Durgun Hydropower Station (48.326732, 92.806310), which has been in operation since 2008 [13]. The station consists of three

Table 1: The number and mean length of tagged grayling at each tagging site, the number captured by gillnets and rod and reel, respectively, and the number of tagged grayling detected throughout the study.

Location	Tag site	# Tagged	Length (mean ± sd, mm)	Net/rod	# detected
Khovd River	ts1	1	440 ± NA	1/0	0
Khovd River	ts2	2	432 ± 25	1/1	1
Khovd River	ts3	7	423 ± 55	3/4	6
Khovd River	ts4	11	430 ± 57	2/9	10
Khar Lake	ts5	11	476 ± 24	5/6	7

Kaplan turbines that are capable of generating 12 MW, although true output has been considerably lower due to the problems with maintenance and the intake of water [14]. A fish-way to allow passage of fish in both up- and downstream directions exists; however, it is nonfunctional due to construction and design deficiencies [14] and therefore has restricted access to spawning habitat for Mongolian grayling [9].

The Shijigtiin Canyon (48.680433, 91.337256), located 140 km upstream from the Khovd River mouth, is the site of a large Chinese–Mongolian hydropower project (the Erdeneburen Dam), construction of which began in 2022. The dam will be 42 m high and impound a large upstream area. Water at the dam will be directed via a headrace canal to a 4-km underground tunnel which will funnel water to the turbines and then reconnect with the old river channel via a tailrace canal (https://erdeneburenhpp.mn/). The power station will have a capacity of 90 MW and is planned to be operational in 2027. The dam is situated just upstream of a known spawning ground for Mongolian grayling (48.668643, 91.337092) at which the relative density and size of spawners have been monitored annually during the last decade as part of an ongoing evaluation program of the dam project (Mendsaikhan et al. unpublished). Plans for two additional large hydropower plants further upstream in the Khovd River system have been reported to be part of an extensive Mongolian hydro-engineering project currently being planned and implemented across the country (the Blue Horse program, [9].

2.2. Sampling and Tagging. Between the 4th and 10th October, 2019, 32 Mongolian grayling (mean ± sd: 444 ± 48 mm, min: 300 mm, max: 552 mm) were caught and tagged at 5 locations along the Khovd River and in the Khar Lake (Figure 1, Table 1). Tagging locations both above and below the Shijigtiin Canyon were chosen to investigate potential upstream and downstream migrations pass the canyon. The Mongolian grayling were caught using rod and reel, as well as with gill nets (mesh size 55 mm) which were actively monitored and retrieved directly once fish were caught. The Mongolian grayling were anesthetized using buffered MS222 and surgically tagged with an acoustic transmitter (Innovasea V9, 9 × 27.5 mm, 2.7 g, signal delay 60 s) in the gastric cavity following the procedures described in [15]. In connection with tagging, the Mongolian grayling were measured and weighted. Tagging took approx. 3 min per fish, where after the fish were allowed to recuperate in cold oxygenated water in the river before release. Water temperatures during tagging were between 8 and 10 C.

2.3. Receiver Deployment. Between the 4th and 10th October, 2019, in connection with tagging, 10 acoustic receivers (Innovasea VR2w and VR2tx) were deployed across the study area; 3 in the Khovd River, 2 in the Khar-Us Lake, 2 in the Chono-Kharaikh River, 1 in the Khar Lake, 1 in the Teel River, and 1 in the Khom River (Figure 1). Receivers were attached to a plastic ring float, connected by a metal wire to an anchor at the bottom consisting of a metal net-pen filled with stones. The receivers were retrieved during September 2020 by using divers as well as draglines, and the detection data were downloaded. In connection with deployment, a detection range test was performed for a receiver deployed immediately upstream the Shijigtiin Canyon (48.722694, 91.337950) in a section of the river that is 160 m wide. The test concluded that more than 90% of signals were detected up to 250 m from the receiver. The receivers also recorded water temperature every 10 min.

2.4. Analysis. To estimate apparent survival of the tagged grayling, the probability of detection within the receiver array over time was described via a Kaplan–Meier estimator and was visualized using a survival curve. For each tagged individual, we calculated the duration between the first and last detection in days. This interval served as an indicator of the time-to-event, where the event is defined as the cessation of detections (or the last detection), potentially indicating the death of the individual. Based on this, the Kaplan–Meier method was used to estimate survival functions for grayling in both River Khovd and Lake Khar systems. To evaluate habitat use and site fidelity, we calculated a Residency Index (RI) for all receivers in the Khovd Khar-Us Lake and Khar Lake networks, respectively. RI was defined as the proportion of monitoring days during which tagged grayling was detected at a given receiver, relative to the total deployment period (4 October 2019–30 October 2020; 393 days). For each receiver, the RI was first calculated per individual fish and then averaged across all fish detected at that receiver. Mean RI values were then summarized by study system and habitat (lake vs. river) to assess whether fish in the two systems differed in their relative use of lake and river environments. All analyses and visualizations were done using the software R [16], using the packages “survival” [17], “ggplot2” [18], and “rayshader” [11].

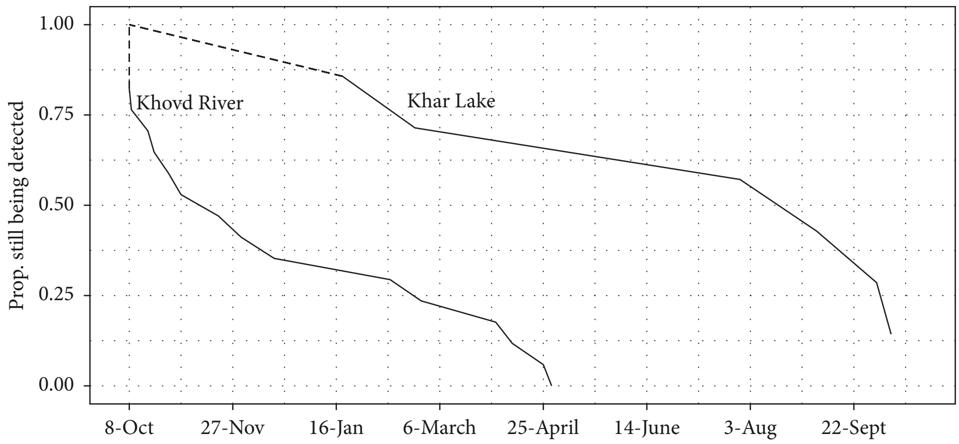

Figure 2: Probability of a tagged Mongolian grayling to be detected within the receiver network over time, as calculated from a Kaplan–Meier survival model based on the last detections for 17 Mongolian grayling tagged in the Khovd River and 7 Mongolian grayling tagged in the Khar Lake. The dashed lines indicate the period until the first detections after release in the Khovd River and in the Khar Lake.

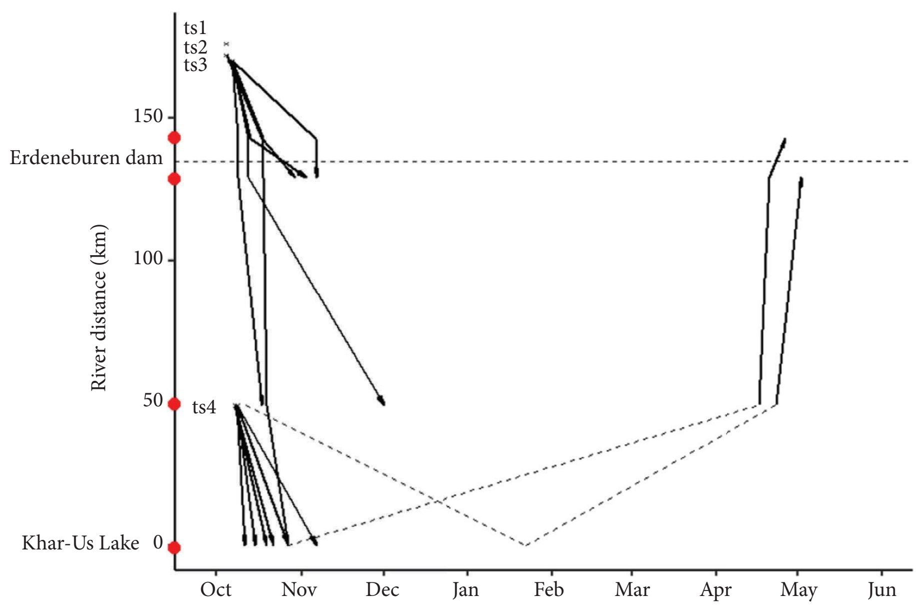

Figure 3: Migration direction and distance of Mongolian grayling tagged in the Khovd River. The horizontal dashed line represents the distance upstream Khar-Us Lake at which the Erdeneburen Dam will be located in the Khovd River. The dashed lines connecting arrow lines intend to highlight the individual Mongolian graylings that performed both downstream and upstream migrations. The symbol *X* represents tagging sites (designated as ts1–4, see Table 1). The red dots along the *y*-axis indicate locations of the receiver.

3. Results

In total, 24 of the 32 tagged Mongolian grayling (75% of the total number of tagged individuals) were detected on at least one receiver after tagging, with an average of 1991 detections per Mongolian grayling over the study period (min: 3, max: 14,642). Of the 8 Mongolian grayling that were not detected, 4 were tagged in the Khovd River and 4 in the Khar Lake (Table 1). About 50% of the Mongolian grayling tagged in the Khovd River was still detected within the receiver network 34 days after release, and the last detection from any of the Mongolian graylings tagged in the Khovd River was made 204 days after release (Figure 2, see Table A1 in appendix for detailed output of the model). About 50% of the Mongolian grayling tagged in the Khar Lake could be detected 314 days after release, and the last detection was made at the end of September, before the retrieval of the receivers (Figure 2).

Of the Mongolian grayling tagged and detected upstream the Shijigtiin Canyon (ts 1–3), all but one migrated downstream passed Erdeneburen during autumn (Figure 3, Table 1). Of the Mongolian grayling tagged and detected below Erdeneburen (ts 4), 7 out of 10 (Figure 3, Table 1) migrated downstream. Downstream migrating was relatively swift, with a mean distance per day of 6.7 km (river distance). One Mongolian grayling was migrated 170 km in 20 days (Figure 3). 8 Mongolian grayling could be confirmed to spend at least part of the winter months in the Khar-Us Lake;

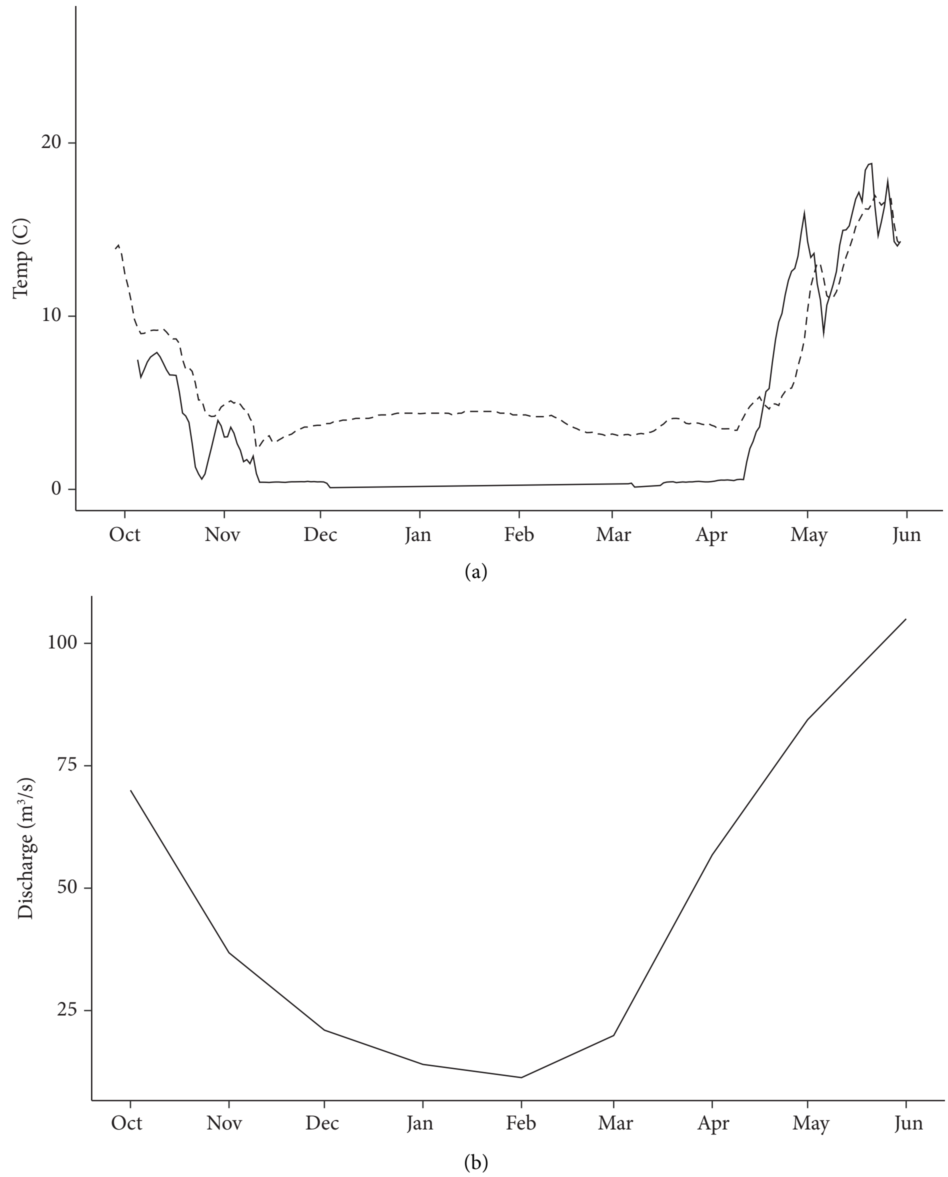

Figure 4: (a) Average daily water temperature measured above the Shijigtiin Canyon (48.723104, 91.338080) in the Khovd River (solid line) and in the Khar-Us Lake (dashed line) (measured at 48.258370 and 92.356032) and (b) average monthly discharge of the Khovd River during the fall of 2019 and spring of 2020.

however, only 2 of these fish were observed to migrate back upstream (Figure 3). Upstream migration occurred during April and May and was swift and directional, with 1 Mongolian grayling confirmed to migrate above the Shijigtiin Canyon (Figure 3).

Both the water temperature and the river discharge varied greatly across fall, winter, and spring. In the river, temperatures approached 0°C during the winter months; however, temperatures in the Khar-Us Lake remained relatively stable around 3-4°C during the same period (Figure 4(a)). Water discharge decreased considerably during winter, with as low as 11 m^3/s in February, and increased 10 fold during spring to over 100 m^3/s in June (Figure 4(b)).

Of the Mongolian grayling tagged and detected in the Khar Lake, all remained in the lake throughout the fall and winter. Of the 5 Mongolian grayling still being frequently detected in spring (Figure 2), each made at least one trip to a tributary between March and May (Figure 5). There were no recorded trips to tributaries either before or after this period.

Monthly RIs varied among receivers and study systems (0.08–0.46). The highest RI values were observed at the Khar Lake receiver (0.46), indicating sustained presence of tagged grayling across months (Figure 6). In contrast, river receivers in both systems showed lower residency (0.08–0.15). Overall, grayling in the Khar System exhibited higher and more lake-dominated residency than those in the Khovd

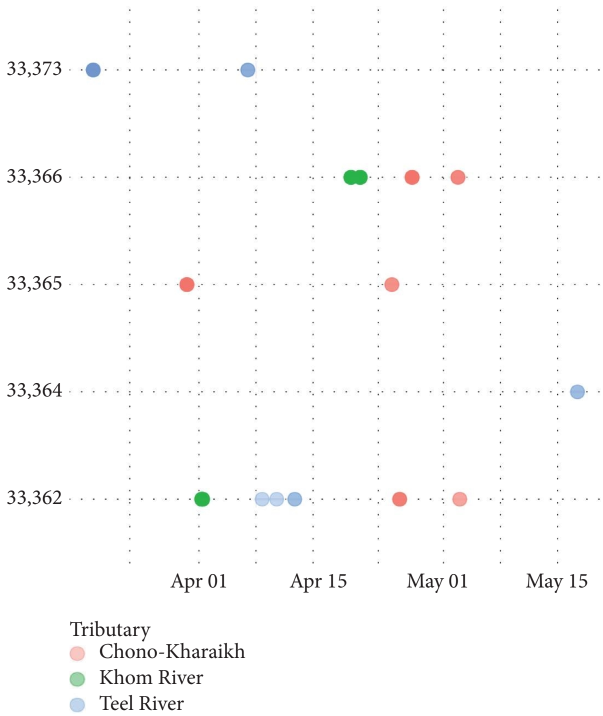

Figure 5: Detections of individual Mongolian graylings tagged in the Khar Lake on receivers in tributaries of the Khar Lake during March to May 2020. April and May constitute potential spawning period for the grayling.

System, where residency was generally low and more evenly distributed between lake and river habitats.

4. Discussion

This study is the first to investigate the migration behavior of Mongolian grayling using acoustic telemetry. Very limited information on the behavior and biology of this species is available, and most of the published work is either in Russian or Mongolian language. The Mongolian grayling in the Khovd River displayed distinct and directional migrations during fall and spring, with one individual migrating over 170 km one-way. This is, to our knowledge, the longest migration distance ever described for any grayling species, which highlights the importance of connectivity and habitat accessibility for this species. The fall downstream migration to the Khar-Us Lake might be an adaptive response to seek suitable overwintering conditions as the winter conditions in the river may be harsh. River temperature approached the freezing point at the measuring station upstream the Shijigtiin Canyon, which in combination with very low water flow and thick ice may create unfavorable living conditions during the coldest winter months. The temperature in the Khar-Us Lake was considerably warmer compared to the Khovd River and would provide more stable hydrological conditions during winter.

Downstream migration to seek overwintering habitat in slower deeper water has been described for both European and Arctic grayling (e.g., [19–22] and seems part of a general migratory cycle between wintering habitat, feeding habitat, and spawning habitat commonly observed in grayling [23]. Such pattern reflects the broader life-cycle framework for stream-dwelling fish described by Schlosser [10], in which migrations connect wintering, feeding, and spawning nodes across the river–floodplain/lake mosaic. Upstream migration during spring correlated in time with a rapid increase in temperature and discharge and can be presumed to be associated with spawning. Onset of upstream migration occurs in the middle of April, corresponding to a water temperature of 5°C–7°C, which is in line with what has been observed for both Artic and European grayling [24, 25]. The Mongolian grayling displayed potentially extensive spawning migration, ascending 150 km up the Khovd River. A known spawning ground for Mongolian grayling in the Khovd River is situated just downstream the Shijigtiin Canyon and the prospected Erdeneburen Dam. One of the upstream migrating Mongolian grayling did not pass through the Shijigtiin Canyon and may hence have spawned at this ground. The other grayling did pass Shijigtiin and hence can be presumed to spawn further upstream at spawning grounds not yet located.

The long migration distances observed in this study are likely conservative estimates, given that the receiver array did not allow tracking fish further upstream than above the Shijigtiin Canyon. Also, the fish tagged upstream Shijigtiin in October may very well originate from further upstream of the tagging site and could have been caught and tagged during their downstream migration. This would seem reasonable given that the Mongolian grayling migrated downstream shortly after being tagged. A more extensive receiver network covering the upstream reaches of the Khovd River would allow a full description of the Mongolian grayling's migration cycle in the area and could potentially reveal new spawning sites upstream of the Shijigtiin Canyon. Also, a systematic collection of local knowledge about the Mongolian grayling in River Khovd would likely also provide valuable information about potential spawning grounds in the system.

The probability of detecting individuals within the receiver network decreased substantially over time for the Mongolian grayling tagged in the Khovd River, suggesting high mortality during winter. Using detection probability as a measure of survival may be misleading, as Mongolian grayling may reside outside the detection range of the receiver network. Apparent winter survival was considerably higher for Mongolian grayling in the Khar Lake, since close to 70% of the Mongolian grayling tagged in the lake were still active beginning of April. This estimate should be considered conservative, and the rapid decline in the proportion of detected individuals starting at the end of August is likely an artefact of the receiver network being retrieved from the study area during September, hence not allowing enough time for further detections of active individuals. Few estimates of annual survival of adult Mongolian grayling exist. Annual survival of European grayling > 18 cm was estimated to 44% in a regulated river in northern Sweden [26], and similar estimates for Arctic grayling in pristine river systems in Alaska range between 51% and 71% [27, 28]. Abundant subsistence and commercial fishing using primarily gillnets

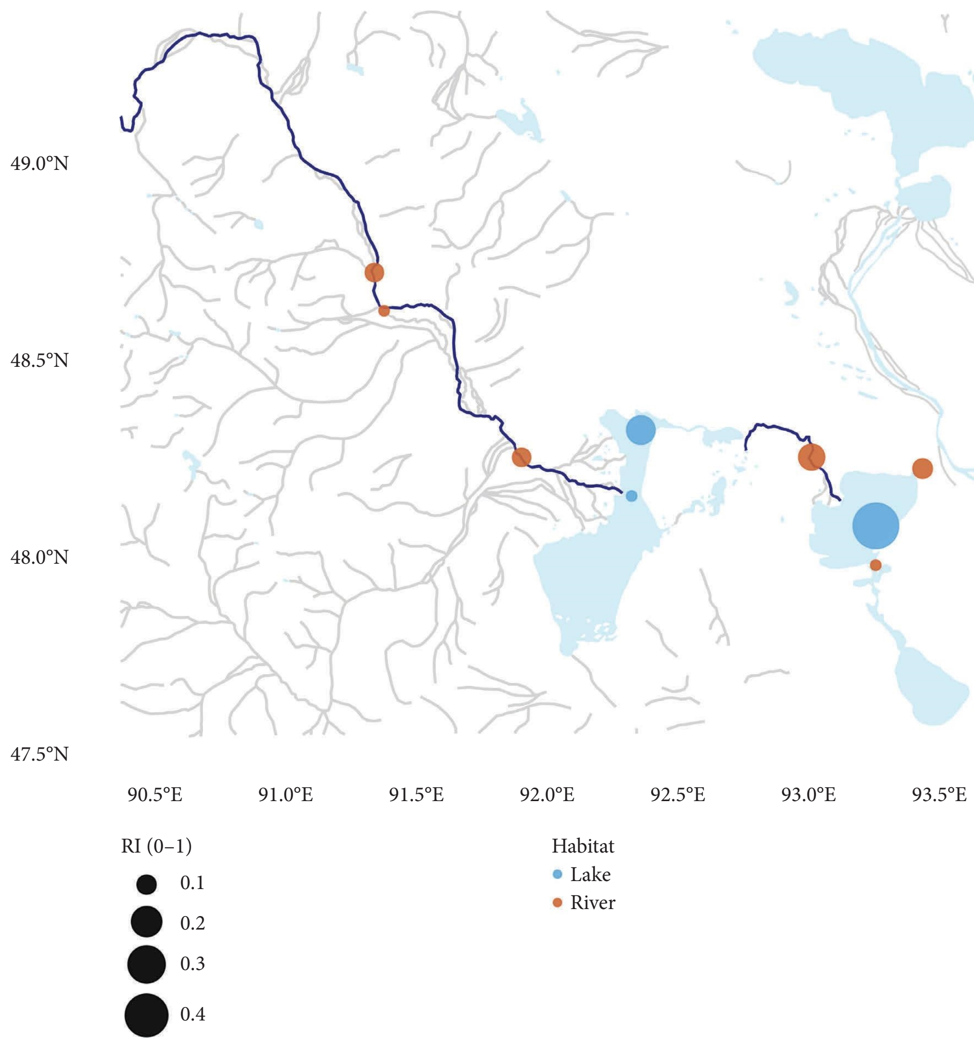

Figure 6: Receiver-level monthly Residency Index (RI) in the study systems. Circle size represents the proportion of months with detections at each receiver, and color indicates habitat type (lake or river).

occur in the Khar-Us Lake during winter, which may contribute to the apparent low survival of the Khovd River Mongolian grayling seen in this study; however, no reliable data exist to validate such claim, and one should note that fishing also occur in the Khar Lake where survival was considerably higher.

The Mongolian grayling in the Khar Lake seems to be part of an extensively lake-dwelling population, and the tagged fish seem to only reside in the tributaries during a short period in the spring (primarily April). Similar behavior has been observed for lake-dwelling European grayling in Scandinavia [20]. The spring migration to the tributaries may be assumed to be associated with spawning, and it is interesting that a few of the tagged individuals visited several tributaries during this period, suggesting potential straying behavior. It is also possible that these movements are linked to the exploitation of seasonal food resources in other streams, such as local macroinvertebrate hatches or spawning aggregations of the sympatric stone loach or Altai Osman. The monthly residency analysis revealed contrasting habitat use between systems. Grayling in the Khar system showed prolonged occupancy of the lake and limited use of connected rivers, whereas grayling in the Khovd–Khar-Us system exhibited lower and more balanced RI values across lake and river sites, indicating more transient use and stronger connectivity between habitats. These differences likely reflect the much larger size and complexity of the Khovd River compared to the smaller Khar Lake tributaries, which provide more diverse habitats and greater spatial opportunities for grayling to exploit throughout the year.

The detections showed that the Mongolian grayling may still utilize the Chono-Karaikh River as spawning habitat, despite the presence of the Durgun power station further upstream. This study lack the spatial resolution to determine where potential spawning occurs in the Chono-Karaikh River; however, such information would be valuable to better understand potential impact of altered flow regimes from power production on the population [29]. Without well-functioning fish passage infrastructure for both up- and downstream movement, the Erdeneburen Dam will likely present an insurmountable migration barrier for the

Mongolian grayling. The consequences of this may be severe, as it will hinder the Mongolian grayling to complete their migration cycle between wintering and spawning habitat. For migratory fish, such disruption may cause the population or species to go extinct, and it is likely that the population native to the lower 200 km of the river will be severely impacted, and potentially collapsing. This is not only due to restricted access to habitat but also due to an altered flow regime below the power station, which may decrease the viability of important spawning grounds just downstream the Shijigtiin Canyon due to, e.g., hydropeaking exposing eggs and spawning habitat to air. Based on the extensive migration behavior observed in this study, one could assume that, if the plans for further hydropower development in the upper reaches of the Khovd River is realized (as outlined in the Blue Horse program [9]), then a severe decline of the majority of the Mongolian grayling populations in the Khovd River system could be expected. This study indicates that the Mongolian grayling may reside in distinct lake-dwelling populations, where the fish spend the majority of the time in the lake and only utilizing running water for spawning. Such populations may be less impacted by hydropower development, given access to functional spawning habitat in tributaries.

4.1. Implications and Future Research. The Mongolian grayling is likely the largest grayling in the world and differ distinctly from other thymallus species by being a top predator with a morphology adapted to piscivory. Its restricted distribution range makes it very susceptible to anthropogenic impact, and ongoing hydropower development at the heart of its native range may in the long run threaten its very existence. This study has shown that the Mongolian grayling in the Khovd River conduct record long migrations and will likely be severely impacted by the Erdeneburen Dam as the dam would break two critical life-history circuit links: (i) lake–river connectivity required for fall migrations to overwintering habitat and (ii) spring access to upstream spawning site. More research is needed on behavior, ecology, and biology of the Mongolian grayling, including better insights into egg and fry development, juvenile habitat requirements, and trophic interactions with sympatric species. Better knowledge of the basic biology of Mongolian grayling will help to better understand the impact of future resource exploration within its distribution range, as well as on going climate change, and will hopefully facilitate the development of functional mitigation measures and management strategies.

Data Availability Statement

The datasets generated during and/or analyzed during the current study are available from the corresponding author on request.

Ethics Statement

The research was conducted in accordance with the legislation pertaining to animal ethics in Mongolia. The care and use of experimental animals complied with Mongolian animal welfare laws, guidelines, and policies.

Conflicts of Interest

The authors declare no conflicts of interest.

Author Contributions

Bud Mendsaikhan contributed to the conceptualization, methodology, data collection, original draft, project administration, and funding acquisition. Nyambayar Batbayar contributed to the conceptualization, methodology, data collection, review and editing, project administration, and funding acquisition. Burmaa Zambuu contributed to the data collection, review and editing, project administration, and funding acquisition. Daniel Palm contributed to the data collection, review and editing, and project administration. James Losee contributed to the data collection and review and editing. Tomas Brodin contribute to the conceptualization, methodology, data collection, review and editing, project administration, and funding acquisition. Gustav Hellström contributed to the conceptualization, methodology, data collection, original draft, project administration, and funding acquisition.

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Supporting Information

Additional supporting information can be found online in the Supporting Information section. *(Supporting Information)*

The Kaplan–Meier model output is presented in Table A1 in the supporting information of this paper. The table summarizes the time-to-event data, including the number at risk, number of events, number censored, survival probability, standard error of the survival estimate, and the 95% confidence interval bounds (upper and lower) for each recorded time point.

Environmental characteristics across selected locations within the study area are presented in Figure A1 in the supporting information.

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