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Movement Pattern and Habitat Use of the Endangered Brook Barbel (*Barbus caninus*) in a Mediterranean Stream

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ABSTRACT

Understanding the ecology and behaviour of freshwater fish species is essential for effective management and conservation. Within the genus *Barbus*, small-sized mountain species remain understudied despite conservation concerns. In this study, we investigated the movement patterns, habitat use and flow preferences of the endangered species *Barbus caninus* in a Mediterranean mountain stream in northern Italy using passive integrated transponder telemetry. Over a 15-month period, 164 tagged fish were tracked between 2 and 30 times. Most individuals exhibited small home ranges, with a median linear range of 33.7 m, although a few fish moved over hundreds of metres. Fish size did not influence movement patterns. Movements were seasonally variable, with a significantly larger linear range observed during spring compared to other seasons. The barbel showed a weak preference for fast-flowing mesohabitats, and this preference was pronounced during winter. Despite this, *B. caninus* predominantly utilised low-velocity confined zones within hydromorphological units, potentially indicating energetically efficient microhabitat use. These findings shed light on the habitat requirements and movement patterns of an endangered species that inhabits small mountain streams and is subject to numerous anthropogenic threats.

1 | Introduction

Freshwater ecosystems are facing conservation challenges, with approximately one-quarter of freshwater fish species currently threatened (Sayer et al. 2025). Freshwater fish populations are declining at an alarming rate, primarily due to human-induced pressures (IPBES 2019) such as habitat alteration (van Puijenbroek et al. 2019), flow regulation (Merciai et al. 2018), pollution (Dudgeon 2019), invasive species (Britton 2023) and climate change (Barbarossa et al. 2021). Despite these concerning trends, many fish species remain understudied, outlining the urgent need for research on their habitat requirements and responses to stressors to support effective conservation efforts (Smialek et al. 2019; Maasri et al. 2022). Fish movement patterns, behaviour and habitat use influence population dynamics, persistence and productivity (Benitez et al. 2015; Gardner et al. 2015). Consequently, understanding a species' movement ecology is fundamental for guiding effective management practices and developing targeted conservation actions and policy measures (Cooke et al. 2022; Allen and Singh 2016).

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Advances in electronic tagging and telemetry technologies have allowed revealing a remarkable diversity in fish movement behaviours and habitat preferences (Cooke et al. 2022). Even among assumed non-migratory fishes, some species remain confined to small spatial areas, exhibiting limited home ranges and strong site fidelity (Schiavon et al. 2025; Hicks and Servos 2017; Marnane 2000; Nakano et al. 1990), while others travel long distances, demonstrating extensive movements (Chavez et al. 2024; Waldman and Quinn 2022). Understanding the extent and limits of these movement behaviours can directly advise conservation and management actions (Brooks et al. 2017), for example informing habitat restoration (Watz et al. 2019), protected areas management (Zolderdo et al. 2024) and connectivity bottlenecks (De Fries et al. 2023). However, despite its importance, movement ecology remains an understudied field, particularly for smaller, less economically significant fish species (Booth et al. 2013; Smialek et al. 2019; Vøllestad 2023).

The genus *Barbus* is a diverse group of freshwater cyprinid fishes, notable for its species richness in European waters (Machordom and Doadrio 2001; Levin et al. 2019). Research on movement behaviour and habitat use in the genus *Barbus* has predominantly focused on larger fluvio-lacustrine species, such as common barbel, *Barbus barbus*. Studies on this species have documented partial potamodromous behaviour, with adults travelling distances of more than 20 km (Ovidio et al. 2007; De Leeuw and Winter 2008; Panchan et al. 2022) and exhibiting higher nocturnal movement activity (Eggers et al. 2025) and directed in-river spawning migrations (Britton and Pegg 2011). Barbels have also been described to pass fishways at relatively high rates, even outperforming potamodromous salmonids (Bravo-Córdoba et al. 2018; Grimardias et al. 2022). In contrast, smaller rheophilic species within the genus *Barbus* have received very little research attention. In a mark–recapture study, Catalonian barbel (*Barbus haasi*) displayed very limited home ranges with most fish being resident within 20 m, and only a few fish moving over 100 m in a mountain stream (Aparicio and De Sostoa 1999). Differences in *Barbus* movement patterns reflect their ecological and behavioural diversity and highlight the need for broader taxonomic scope of the spatial–ecological research.

The brook barbel (*Barbus caninus* Bonaparte, 1839) is a small rheophilic fish historically widespread in the river basins of northern Italy. This species primarily inhabits the upper reaches of rivers, favouring swift currents in moderately cold waters typical of hilly and sub-alpine streams (Kottelat and Freyhof 2007; Fortini 2016). Once abundant, *B. caninus* now exhibits a fragmented distribution (Tsigenopoulos et al. 2002; Bianco and Delmastro 2004). Like all the other native Italian *Barbus* species, it is listed as endangered on the IUCN Italia Red List (Rondinini et al. 2022). It is at risk due to multiple environmental pressures, including river fragmentation, water abstraction and habitat degradation (Bianco 2003; Bianco and Delmastro 2004; Fortini 2016; Skoulikidis et al. 2017; Belletti et al. 2020) that are challenging also many other Mediterranean *Barbus* species facing population declines (IUCN Red List 2025). Additionally, competition and hybridisation with introduced, non-native barbel species pose further threats (Meraner et al. 2013; Carosi et al. 2017; Ferrari et al. 2025). Despite its conservation status, little is known about the movement ecology and habitat use of *B. caninus*. Nevertheless, to develop effective conservation and management strategies, it is essential to understand the ecology and behaviour of an endangered species, particularly its habitat preferences and movement patterns (Maasri et al. 2022).

This study aimed to investigate the movement patterns and habitat use of *B. caninus* across different temporal scales in a Mediterranean mountain stream. Using passive integrated transponder (PIT) telemetry, we tracked individual *B. caninus* across various stream habitats to quantify their linear range, net travelled distance, habitat use over long-term (462 days), seasonal and diurnal timescales. We also compared mesohabitat flow characteristics with actual water velocities used by tagged individuals as well as diel and seasonal changes in activity.

2 | Materials and Methods

2.1 | Field Research Site

The study was carried out in Rio Morsone, a 5-km-long Apennine Mountain stream located in the Piedmont region, Italy. The Rio Morsone is a tributary to the Lemme River, within the Po basin (44°36′36.5″N, 8°49′01.6″E; Figure 1a). The fish assemblage is dominated by Italian riffle dace (*Telestes muticellus*), with brook barbel (*B. caninus*) as the second most abundant species. Italian chub (*Squalius squalus*) and introduced brown trout (*Salmo trutta*) occur only occasionally and in low numbers. No individuals of Italian barbel (*Barbus plebejus*) were detected within the study area, despite the species being present in the lower reaches of the Rio Morsone and Lemme River. Movements from the Lemme River into the Rio Morsone are obstructed by a series of unpassable weirs located downstream of the study reach. Its absence in the upper reach where this study was conducted reduces the likelihood of hybridisation events within the studied population (Ferrari et al. 2025).

The study reach covers a length of 850 m and is located at elevations ranging from 395 to 421 m a.s.l., with an overall slope of 4%. It averages 3.5 m in width, ranging from a few decimetres in narrow sections to 9 m in the widest pools, with an average water depth of 17.4 cm (SD = 8.4 cm) under average flow. Habitat mapping was conducted using the MesoHABSIM protocol (Parasiewicz 2007; Vezza et al. 2014), following ISO 748 (2021) standards. Discharge measurements were taken on three occasions, representative of average-, low- and high-flow conditions, respectively: March 3, 2022 (17 L s^{-1}), July 14, 2022 (5 L s^{-1}) and January 30, 2023 (54 L s^{-1}). The habitat composition consisted of riffles (38%), pools (32%), glides (19%) and rapids (11%) during average flow conditions. The stream morphology of the study reach remains unaltered by anthropogenic activities, and no artificial barriers impede fish movement. However, the lower section experiences intermittent flow during low-flow conditions, which limits downstream movement both within the reach and beyond it (Schiavon et al. 2024). Water temperature and levels were continuously monitored throughout the study using a HOBO MX2001 sensor set to record at 20-min intervals (Figure 2).

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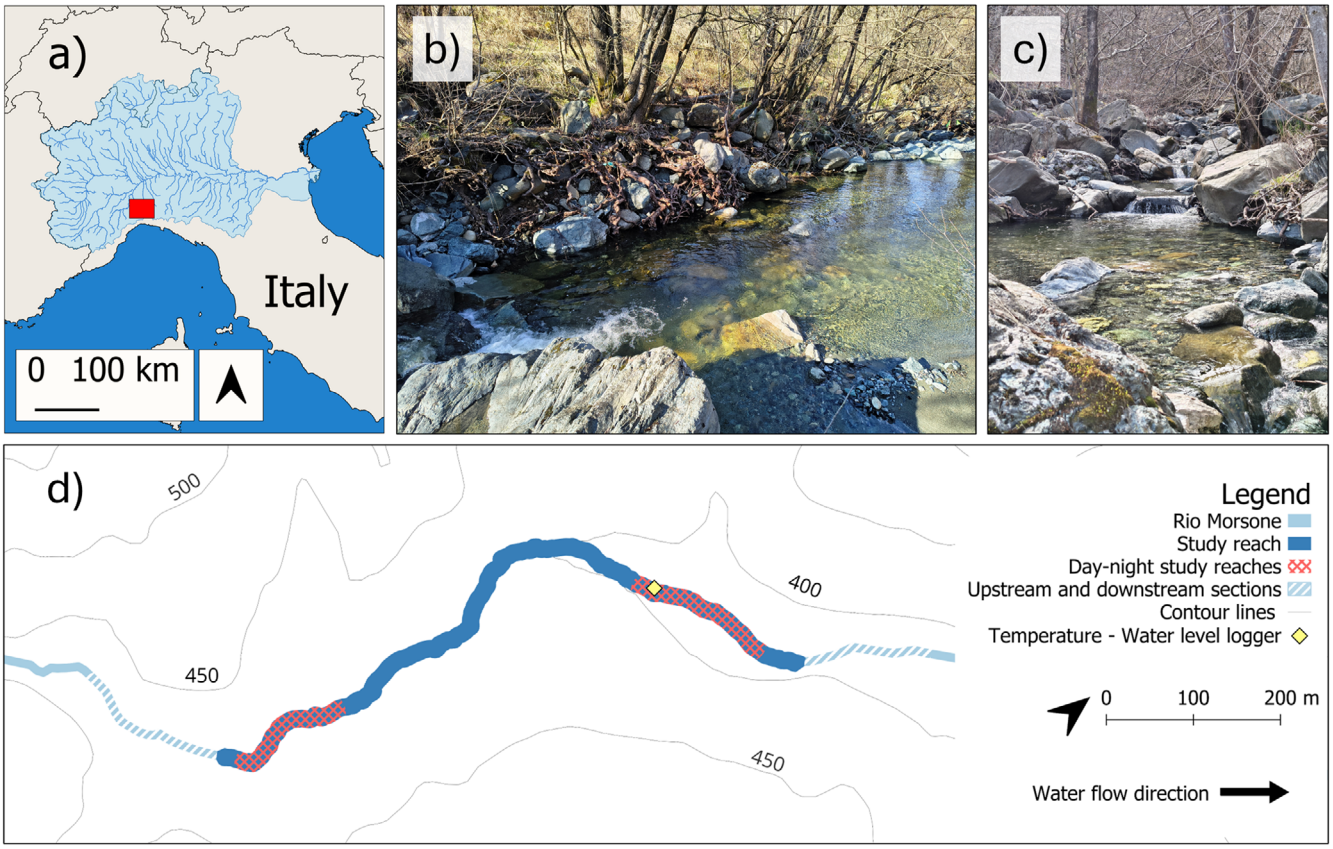

FIGURE 1 | (a) Location of the study area within the Po River watershed in northern Italy. (b, c) Photos of the study reach, taken in spring 2025. (d) Map of the study reach along the Rio Morsone. The study reach is shown in dark blue, with the day–night studied reaches marked by red-blue cross-hatching. Dashed sections upstream and downstream of the studied reach represent occasionally monitored areas during the study period. Contour lines indicate elevation changes with an interval of 50 m. The yellow square indicates water-level and temperature logger location.

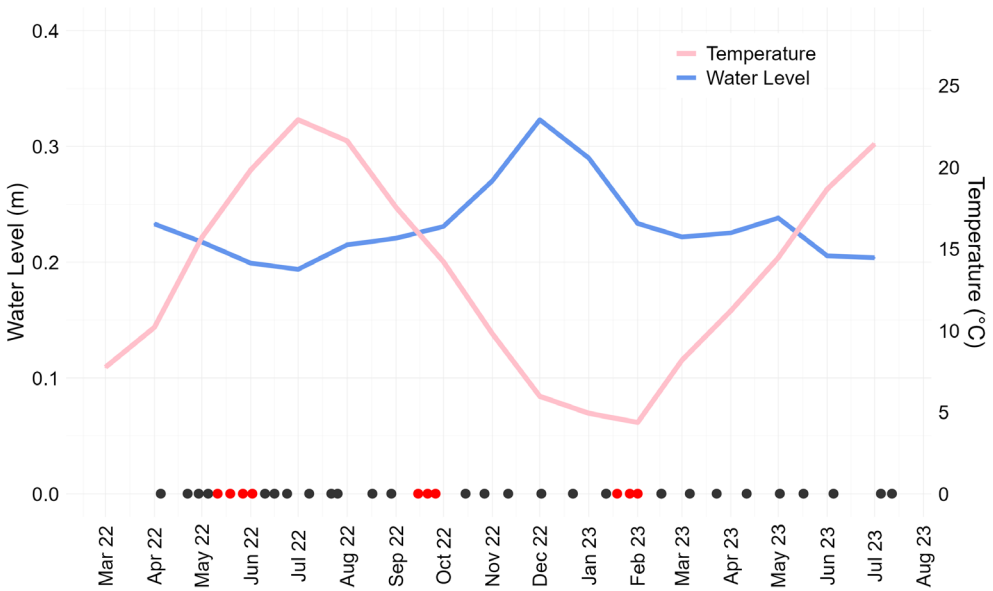

FIGURE 2 | Monthly averages of water level and temperature were recorded throughout the study period (March 2022–July 2023) in the lower section of the study reach (Figure 1). Tracking event dates are indicated by black dots on the *x*-axis, whereas red dots represent paired day–night tracking events.

2.2 | PIT Telemetry

In March and October 2022, a total of 200 *B. caninus* were captured by electrofishing across the entire study reach and tagged with passive integrated transponders (PIT tags; Oregon RFID, USA; 12 × 2.1 mm; 0.10 g). Healthy fish over 6 cm in length were selected for tagging. PIT-tagged *B. caninus* of this size have been shown not to differ from untagged individuals in survival

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or behaviour (Nyqvist et al. 2024) and likely overlaps with the lower size ranges for which sexual maturity occurs (Kottelat and Freyhof 2007; Fortini 2016).

Prior to tagging, fish were anaesthetised in a clove oil solution (0.2 mL L^{-1}; Aroma Labs, Kalamazoo, MI, USA). A 2–3 mm ventral incision, positioned just ahead of the pelvic fins and slightly off the ventral midline, allowed insertion of the transmitter into the body cavity (Schiavon et al. 2023; Nyqvist et al. 2024). Tagged individuals were then weighed and measured for fork length before being transferred to river-water recovery tanks. Following a 30-min recuperation period, all fish were returned to their original capture sites.

Between April 2022 and July 2023, fish were tracked during 37 tracking events (Figure 2). Tracking methods followed the procedures detailed in Schiavon et al. (2024). We used a mobile backpack antenna (Mobile HDX Long Range PIT Tag Reader Kit; Oregon RFID) and a portable pole antenna to detect tagged fish throughout the study reach. We walked or waded upstream, scanning the full width of the channel (Schiavon et al. 2025). For real-time visualisation of PIT codes, the reader was paired via Bluetooth to an Android smartphone running Serial Bluetooth Terminal (v. 1.42). To minimise behavioural disturbance to fish, surveyors remained on the streambank whenever possible, entering the wetted channel only in wider reaches when necessary and avoiding wading in narrow sections. For each detection, we recorded the date, time and position in a hydromorphological-unit coordinate system (using a handheld laser rangefinder, TruPulse 360R; Laser Technology), and any observed live fish activity or movements were recorded. Ten additional paired day–night tracking sessions were conducted in two subsections of the river (Figure 1d) to study movements over short distance and difference in habitat use between day and night. Day–night tracking included four events in spring 2022, three from late summer to early autumn 2022 and three during winter 2023 (Figure 2). Additionally, areas approximately 150-m upstream and downstream of the main study reach were occasionally tracked to capture dispersal beyond the study reach (Figure 1d).

2.3 | Data Analysis

For this study, only *B. caninus* individuals confirmed as alive and with a minimum of two detections were included, following the methodology outlined by Schiavon et al. (2025). An alive fish was defined by visual detection or upstream movements necessitating active swimming. For spatial analysis, fish positions recorded during field tracking were transformed into linear positions using the QGIS LRS plugin (LRS, version 1.2.3, retrieved from http://blazek.github.io/lrs/). Linear positions were then used to calculate movement metrics, including linear range, calculated as the maximum distance between an individual's furthest upstream and furthest downstream detected positions over the studied period, and the net travelled distance, which represents the directional displacement between the first and last detections over the study period (Capra et al. 2018; Schiavon et al. 2025).

2.3.1 | Movement Pattern and Habitat Use

The effects of fish length and season (spring: March 21–June 20; summer: June 21–September 22; autumn: September 23–December 20; winter: December 21–March 20) on the log-transformed linear range were analysed using linear mixed models (LMMs). Individual fish identification codes (ID) were included as a random effect to account for repeated measures of the same fish. To control for potential biases due to the number of positions, seasonal detection counts were incorporated into the models. Habitat use was quantified as the proportion of average detections per fish in each mesohabitat category, whereas habitat preference focused on fast-flowing habitat (riffle and rapid proportions merged). Fast-flowing habitat availability was estimated through habitat mapping conducted under high-, average- and low-flow conditions. Habitat availability per season was then obtained by weighing flow conditions during tracking sessions within respective seasons. Fast flow habitat preference per season was tested using a Wilcoxon signed-rank test where observed fast-flowing habitat use was compared with available fast-flowing habitat in the four seasons. A generalised linear mixed model (GLMM) with a binomial error distribution (fast-flowing habitats: yes/no for each fish position) was used to assess the effects of fish size and linear range, both scaled on fast-flowing habitat use. Fish ID was included as a random effect to account for repeated measures, and continuous variables (fish size and linear range) were standardised prior to modelling.

2.3.2 | Day–Night Movement

Day–night movement was quantified as the linear distance in metres between paired day and night positions recorded during the 10 tracking sessions. Summary statistics, including median, interquartile range (IQR), minimum and maximum values, were calculated for each season (spring, late summer and winter) across observations. The influence of fish size (length) and season on log-transformed day–night movement was analysed using an LMM, with fish ID included as a random effect. The effect of day/night on habitat use, fast-flowing habitat use (binary: 1/0) was analysed using a GLMM, with fish ID as a random effect. To capture seasonal differences in diel habitat use, the model included an interaction between day/night and season (spring, late summer and winter). To further investigate activity patterns, data on seen (active) and not-seen (sheltering/inactive) fish were used to test for differences in activity between day and night. The effect of day/night and season on observed activity (seen yes/no) was analysed using a GLMM, with fish ID included as a random effect.

2.3.3 | Flow Velocity Preference

During manual tracking events on July 5 and July 10, 2023 (low-flow conditions), direct measurements of local flow velocities were carried out at locations where tagged *B. caninus* individuals were detected. Fish exhibited varied behavioural responses upon detection: some individuals actively moved in search of refuges, whereas others remained stationary, either frozen on the

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substrate or continuing their foraging behaviour undisturbed. The first precise position where each fish was detected was then used to measure local flow velocities using an electromagnetic flowmeter (Seba Hydrometrie FlowSens) at half the water depth. In shallow areas, near-bottom flow velocities were recorded. A total of 70 flow velocity measurements at precise fish locations were collected, covering 51 fish individuals. To avoid intra-individual correlation, the analyses were performed using only the first recorded flow velocity for each individual. A Mann–Whitney *U* test was conducted to compare the flow velocity at the precise fish location with the mean velocity at the specific habitat unit where the fish was detected (based on the values measured during habitat mapping at low-flow conditions). As the pools contained predominantly zero velocity zones, the comparisons were performed on pool data and flowing habitats (glides and fast-flowing types) separately. The non-parametric approach was applied due to the data not meeting the assumptions for parametric testing. The relationship between flow velocity measure and fish length was tested using linear regression.

2.3.4 | Software and Tools

Statistical analyses were conducted in RStudio (version 2022.02.0; R Core Team 2022). Geospatial data processing was performed using QGIS (version 3.24.3-Tisler). Data analyses utilised the lme4 package (Bates et al. 2015) and lmerTest (Kuznetsova et al. 2017), whereas mixed-effects model validations were conducted using the DHARMa package (Hartig and Hartig 2017).

3 | Results

3.1 | Movement Pattern and Habitat Use

In total, 164 out of 200 tagged fish in Rio Morsone (Table 1 and Table S1) were tracked alive between 2 and 30 times during the study period, with a median of seven detections (IQR = 5–10), while 36 individuals were either never detected or detected only once. The interval between the first and last detections ranged from 15 to 462 days, with a median duration of 197 days (min–max = 15–462 days, IQR: 129–244 days). The tracked fish exhibited a median linear home range of 33.7 m (min–max = 0.5–320.8 m, IQR: 18.5–76.5 m).

Most of the fish (37%) remained within a localised area of ±10 m, while 31% moved upstream and 32% moved downstream from first to last detection. The linear range distribution (Figure 3) exhibited strong leptokurtosis (kurtosis = 7.2) and pronounced positive skewness (skewness = 12.0). Among fish observed for over a year, a similar pattern was noted, with leptokurtosis (kurtosis = 3.5) and positive skewness (skewness = 1.3). The linear home range for this group averaged 34.7 m, with values ranging from 5.2 to 257.6 m (IQR: 25.2–91.5 m; $n = 24$) with a median of 17.5 detections (IQR = 11.5–22.5).

Linear range was significantly higher in spring (Figure 4) compared to the baseline season, autumn (LMM, estimate = 0.686, $p < 0.001$). No significant differences were observed between autumn and summer ($p = 0.243$) or autumn and winter ($p = 0.498$). Additionally, the number of detections had a weak but significant effect on the linear range, with more detections associated with a slightly larger range (estimate = 0.104, $p = 0.008$). Fish length did not have a significant effect on linear range (estimate = 0.008, $p = 0.083$).

Fish were tracked across all four available habitat types: pools (mean proportion = 33.0%), glides (12.4%), riffles (41.8%) and rapids (12.8%). Observed use of fast-flowing habitats (riffles and rapids) was significantly higher than available habitats during winter (Wilcoxon, $V = 14{,}988$, $p = 0.001$, $n = 123$) but not during autumn, spring or summer (Wilcoxon, $V = 11{,}058$, $p = 0.2581$ for autumn; $V = 18{,}563$, $p = 0.403$ for spring and $V = 5263$, $p = 0.190$ for summer). The GLMM revealed no significant effects of size or linear range as predictors for detections in fast-flowing habitats (linear range: estimate = −0.017, $p = 0.879$; size (length): estimate = 0.102, $p = 0.361$). However, a positive intercept suggested a slightly higher overall likelihood of being found in fast-flowing water (estimate = 0.223, $p = 0.041$; Figure 5).

3.2 | Day–Night Movement

The overall median of all paired day–night movement values across all observations was 1.9 m (min–max: 0–25.0 m; IQR: 0.2–4.9 m, $n = 86$). In spring, the median day–night movement across observations was 3 m (IQR: 1–10.5 m, range: 0–25 m, $n = 27$). In late summer, the median was 2 m (IQR: 0.875–5.25 m, range: 0–20.7 m, $n = 16$). In winter, the median was 0.9 m (IQR: 0–2 m, range: 0–22.4 m, $n = 43$). No significant effect of fish size (length) on the extent of day–night movements was observed (LMM; coefficient estimate = −0.0079, $p = 0.336$, $n = 84$). However, the extent of day–night movement was significantly higher in spring compared to winter (LMM; coefficient estimate = 0.616, $p = 0.010$), indicating diminished movement activity during the colder season. A tendency for higher movement in late summer than winter was also seen (LMM; coefficient estimate = 0.522, $p = 0.056$). Fish were more active (likely to be visually observed) at night compared to day (GLMM; estimate = 2.068, $p < 0.001$), and in late summer (estimate = 3.013, $p < 0.001$) and spring (estimate = 2.709, $p < 0.001$) compared to winter.

TABLE 1 | Summary of biometric measurements (fork length and wet mass) for the 164 individuals tagged in March and October 2022 and included in the analysis. The biometric measurements for two individuals tagged in March 2022 are missing.

	Length (mm)				Mass (g)				
	Median	IQR	Min	Max	Median	IQR	Min	Max	*n*
March	76	72–95	60	129	5.3	4.2–10.1	2.6	29	73
October	77	70–88	60	133	5.0	3.7–7.4	2.5	25.6	91

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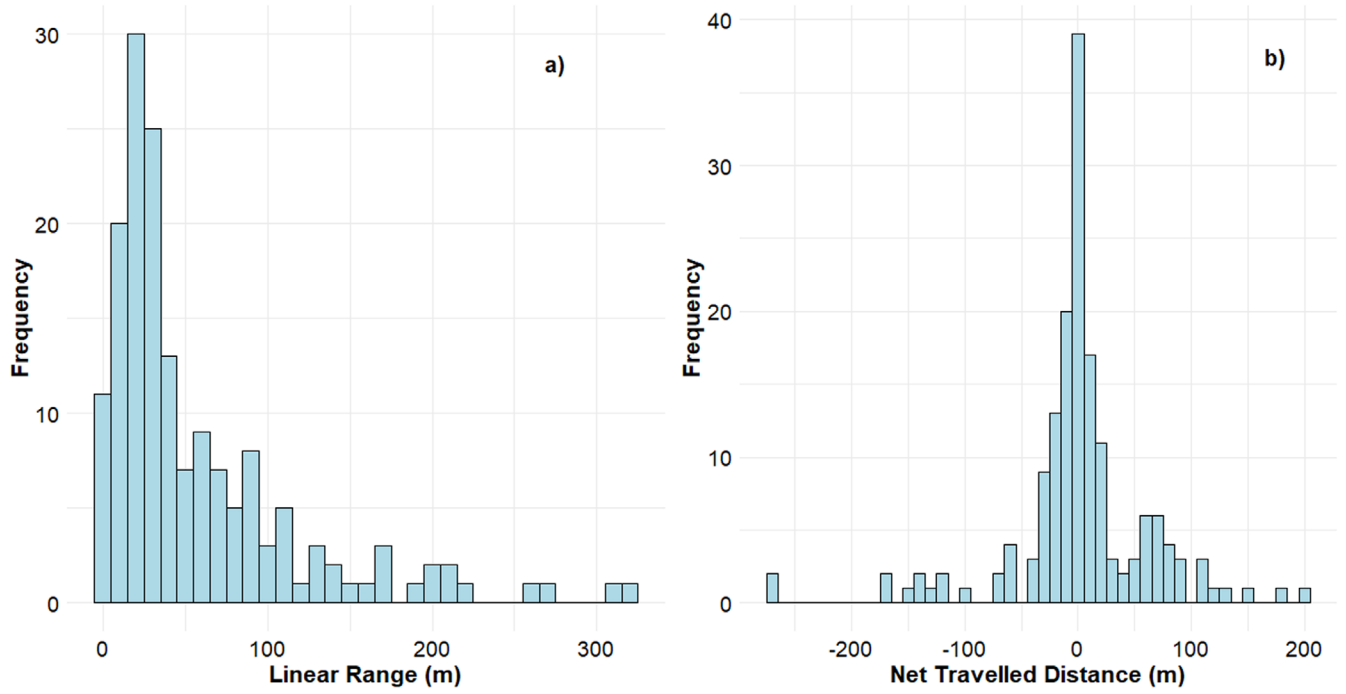

FIGURE 3 | Frequency distributions of movement metrics for 164 *B. caninus* individuals in the Rio Morsone. (a) Linear range distribution shows the restricted movement of the population, with a leptokurtic distribution. The *x*-axis represents the linear range (m), whereas the *y*-axis indicates the number of individuals. (b) Net travelled distance distribution illustrates upstream movements (positive values) and downstream movements (negative values), with the *x*-axis showing net travelled distance (m) and the *y*-axis indicating frequency.

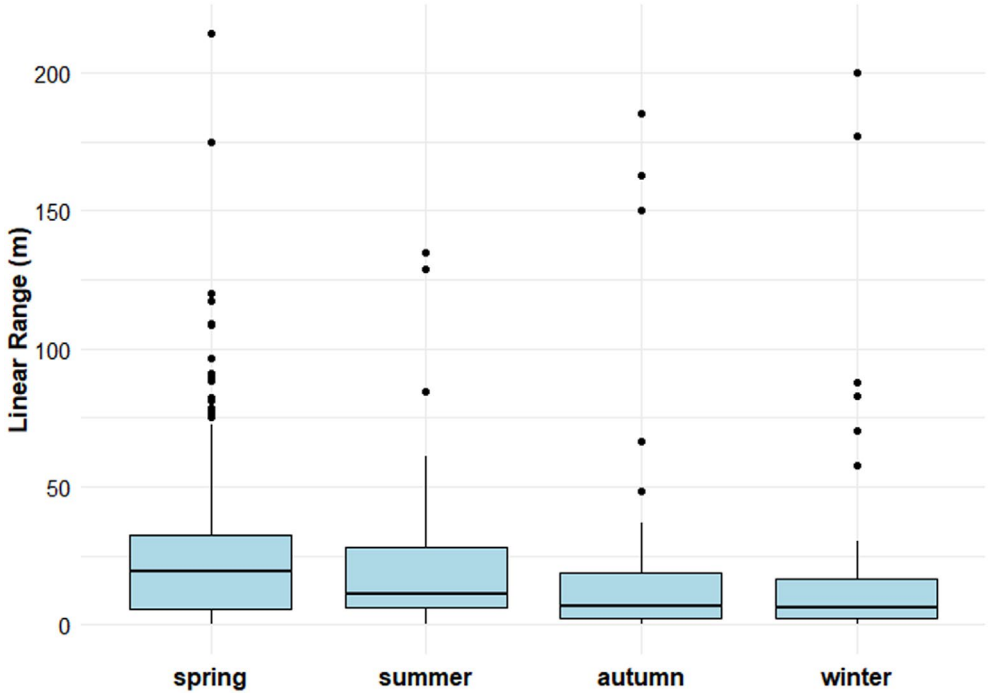

FIGURE 4 | Box plots illustrating seasonal variations in the linear range (m) of *B. caninus*. Each box represents the interquartile range (IQR) of linear ranges for each season, with whiskers extending to 1.5 times the IQR. The median values are shown as horizontal lines within each box.

3.3 | Flow Velocity Preference

In the analysis of water velocities at the detection points of individual *B. caninus* across all habitat types within the river section, the median flow velocity was 0.015 m/s (min–max: 0.001–0.210 m/s; IQR: 0.004–0.030 m/s; $n = 70$), highlighting their positioning within slow-flow small-scale environmental conditions in every habitat type, even when the overall habitat exhibited higher average water velocities. A Mann–Whitney *U* test comparing flow velocity at fish locations with the mean

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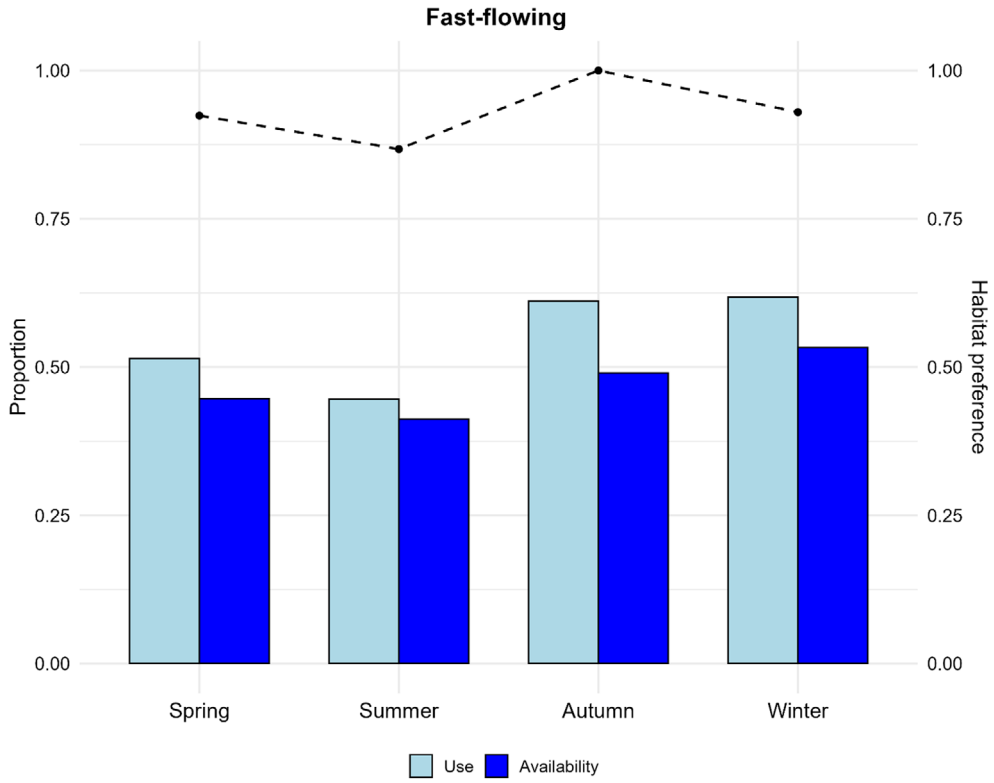

FIGURE 5 | Bar plots of habitat use, availability and preference for fast-flowing habitats (riffles and rapids). Light blue bars show the mean proportion of fish locations within each habitat type; dark blue bars show the proportion of each habitat type available. The dashed line with black circles plots the preference index (use/availability) normalised to a 0–1 scale (Bunt et al. 2021). To derive habitat availability, each manual tracking event together with its associated flow condition was weighted according to how frequently it occurred, the manual tracking events were distributed as follows: spring ($n = 15$), summer ($n = 10$), autumn ($n = 5$) and winter ($n = 7$).

habitat velocities revealed a statistically significant difference in flowing water habitats ($W = 200$, $p = 0.0045$, $n = 27$), with fish occupying areas of lower water velocity compared to the habitat's mean, while no significant difference was found in pool habitats ($W = 291$, $p = 0.9575$, $n = 24$). Linear regression analysis demonstrated that fish length did not affect the observed flow velocities at these positions ($R^2 = 0.010$, $p = 0.483$, $n = 51$).

4 | Discussion

Barbus caninus predominantly exhibited stationary behaviour with a median linear range of 33.7 m. Only a few individuals displayed a longer range of movement, reaching up to 321 m. This pattern of limited linear range was consistent for fish monitored over a long-term period of 1 year and was not just an artefact of short-term monitoring. Compared to the other seasons, the fish showed a greater range of movement in general and between day and night in spring. They preferred faster flowing water in winter, while their distribution across fast-flowing habitat types did not differ from that of the available habitat during the rest of the year. Fish size or time of day did not influence habitat use. Within the mesohabitat, fish used locations with flow velocity lower than the average stream section flow. Within a site, fish were more active (as opposed to sheltering) at night than during the day, and in spring and late summer than in winter. The predominantly stationary behaviour observed aligns with previous studies showing that populations are typically composed of a small mobile fraction and a larger resident fraction (Rodríguez 2002; Knaepkens et al. 2004; De Leeuw and Winter 2008; Radinger and Wolter 2014). Limited home ranges could be a result of high local habitat diversity in the stream, as fish are able to feed, overwinter, and reproduce within a limited stream reach (Nakano et al. 1990; De Leeuw and Winter 2008; Britton and Pegg 2011; Schiavon et al. 2025). Residency may also provide benefits in terms of familiarity with shelters, feeding opportunities, conspecifics and predation threats (Nakano et al. 1990). The mobile fish, although few, on the other hand enhance population connectivity, enabling resource acquisition, competition avoidance and resilience to environmental changes (Gowan 2007). Particularly, upstream movers are essential for maintaining population dynamics and reducing the risk of local extinction in the upper reaches of rivers as older individuals offset downstream drift of early life stages, ensuring population stability and connectivity (Humphries and Ruxton 2002; Chavez et al. 2024). Among the movers in this study, an almost equal number of fish were observed moving upstream and downstream.

The restricted movement patterns found for *B. caninus* in this study align with similar movement behaviour of the Italian riffle dace in the same system (Schiavon et al. 2025). Concerning other barbel species, a mark-and-recapture study on the Catalonian barbel indicated a similar result (Aparicio and De Sostoa 1999), albeit with a much lower temporal resolution. These stream barbels were mostly recaptured within

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10 m of their release site. The results from Aparicio and De Sostoa (1999) and our study, however, contrast with studies on larger barbel in larger rivers. For example, the broader fluvio-lacustrine home ranges observed in common barbel, *B. barbus*, in a larger river, are on the scale of kilometres (De Leeuw and Winter 2008; Capra et al. 2018). Just for spawning, these large barbels are known to travel distances of up to 40 km (Panchan et al. 2022). Relatively short movement ranges (100s of metres) have, however, been reported also for common barbel in larger rivers, at least during limited tracking periods (Eggers et al. 2025). Directed spawning migrations have been reported for *B. barbus*, and described also for *B. caninus* (Bianco 2003; Bianco and Delmastro 2004). We found no evidence of such extensive spawning migrations in this study. Instead, the modest increase in linear range observed in spring may have resulted from heightened activity associated with searching for suitable spawning sites. While brief movements, such as short-term return migrations lasting only a few days (Fredrich et al. 2003) may have escaped detection within our tracking interval, the lack of long-distance dispersal is likely attributable to the stream's hydromorphological richness, which provides a diversity of easily accessible spawning habitats along the study reach (De Leeuw and Winter 2008).

Barbus caninus exploits a variety of habitats, including pools, riffles and rapids. Interestingly, a slight habitat shift was observed during the winter season, with a higher frequency of detections in riffle and rapid habitats compared to other seasons. This shift coincided with increased water flow levels, likely expanding the availability of these fast-flowing habitats. However, even after accounting for the increased habitat availability in winter, the higher detection rates in fast-flowing water suggest a slight behavioural preference. In summer, the fish tended to increase their occupancy of pools (the inverse of fast-flowing habitat use). This behaviour is likely driven by the reduced availability of fast-flowing, shallow habitats during this period, triggering the fish to move into deeper, more stable and permanent river sections. Additionally, deeper sections may provide cooler, thermally stable refuges (Frechette et al. 2018). These combined factors, the limited shallow fast-flowing habitat availability, the need for thermal refuge and the necessity to escape intermittent reaches (Aparicio and De Sostoa 1999; Pires et al. 2014) likely contribute to this observation. However, further studies are needed to determine the primary driver of this behaviour. Inter-specific interactions can also influence the movement and habitat use, particularly when mediated through aggressive interactions (Chapman 1962; Nakano 1995). Aggressive behaviour is not considered a significant factor in *B. caninus* behaviour. In fact, no such interactions were noted in this study, nor have they been documented in prior laboratory studies (Nyqvist et al. 2024). The fact that size did not influence movement or habitat use could indicate the limited importance of inter-specific interactions and it also suggests that, within the size range studied (> 6 cm), no important ontogenetic habitat requirements occur (Gowan and Fausch 2002).

The analysis of day–night movement patterns in *B. caninus* revealed minimal movement and no difference in habitat use between day and night. The maximum recorded diel net movement was limited to 25 m. The consistent use of habitats throughout the diel cycle suggests that *B. caninus* predominantly occupied stable positions offering readily available resources and refuges. This behaviour contrasts with findings in other species, such as substantial diel movements reported in *Catostomus* species by Booth et al. (2013) and shifts from slow to fast-flowing water in cutthroat trout (Hilderbrand and Kershner 2004). Similar, as for the seasonal movement patterns, the limited range of movement observed during the 10-paired day and night tracking sessions in *B. caninus* may again be explained by the heterogeneity of its habitats, which provide sufficient feeding opportunities and refuges within short distances. This localised habitat availability likely reduces the requirement for extensive nocturnal movements. The fish did, however, display increased activity during night while exhibiting a higher tendency to shelter during the day. A similar behaviour has been reported for bull trout (*Salvelinus confluentus*) that emerged to feed in shallow areas during the night while remaining concealed during the day, presumably as a predation avoidance strategy (Muhlfeld et al. 2003). Also, other salmonids (Heggenes et al. 1993; Kambestad et al. 2022) and sculpins (Greenberg and Holtzman 1987) have been reported to remain sheltered during the day and emerged to feed at night. This is also in line with increased movement activity at night for other barbel across various life stages (Copp et al. 2002; Eggers et al. 2025). Iberian barbel, for example, show a preference to migrate at night (Santos et al. 2005). Over the year, the tagged fish were also less active and more likely to shelter in winter compared to autumn and spring. This is in line with literature documenting decreased winter activity in the *Barbus* genus (Baras 1995; Lucas and Batley 1996), and in many other fish species. In winter, reduced metabolic rates reduce the energy requirement while lower swimming performance increases the predation risk (Shuter et al. 2012), especially in relation to warm-blooded predators such as birds and mammals (Watz and Piccolo 2011; Watz et al. 2016). Higher water levels, associated with more difficulties to observe fish, might, however, also have contributed to the lower activity levels observed in winter.

Interestingly, *B. caninus* demonstrated a clear preference for areas with lower flow velocities relative to the mean flow velocity of the habitat types where it was observed; the species selectively occupied micro-scale areas with reduced water velocity. This behaviour likely represents an adaptation to balance energy expenditure with resource acquisition in high-flow environments (Piccolo et al. 2008). Small-bodied fish like *B. caninus* can easily exploit localised low-velocity zones compared to larger fish (Knapp et al. 2019). As a benthic species, *B. caninus* likely uses even slower boundary layers near the substrate, further reducing flow velocity and energy expenditure compared to the velocity being measured at mid-water depth. It is important to note that this analysis was conducted during the summer of 2023, a period characterised by reduced water velocities in the studied river section due to low-flow conditions. These findings provide first insights into the flow preferences of *B. caninus* and warrant further investigation; in particular, research across all seasons is needed to fully understand the energetic advantages and habitat preferences of *B. caninus* under varying flow conditions. The fact that the actual hydrodynamic used differs from that assigned to the fish based on mesohabitat features can have implications for both habitat models (Parasiewicz 2007; Vezza

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et al. 2014; Negro et al. 2021) and individual-based behavioural modelling (Mawer et al. 2023) as average conditions do not always correspond to conditions experienced by the fish.

5 | Conclusion

The study revealed that *B. caninus* predominantly exhibited stationary behaviour, and most individuals displayed strong site fidelity, relying on localised habitats that are likely to offer diverse and accessible resources. Movement patterns were highly restricted, with diel shifts limited to a few metres. Seasonal variations showed slightly increased activity in spring, but movements remained confined to localised areas without evidence of extensive spawning migrations. A small mobile fraction of *B. caninus* likely plays a crucial role in maintaining population connectivity, genetic flow and recolonisation of habitats (Humphries and Ruxton 2002). These mobile individuals contribute to the species' resilience against environmental changes, emphasising the importance of longitudinal connectivity in both upstream and downstream directions, even in a predominantly resident fish population (De Fries et al. 2022). To safeguard *B. caninus*, conservation efforts must focus on preserving habitat heterogeneity and ensuring longitudinal connectivity. Such measures will support both sedentary and mobile individuals, facilitating dispersal, recolonisation and long-term population stability. By implementing these strategies, the conservation of endangered *B. caninus* in its ecosystem can be effectively improved.

Author Contributions

Conceptualization: A.C., A.S., C.C., D.N., J.W. Data collection: A.C., A.S., D.N., M.S. Data analysis: A.S., D.N., J.W. Manuscript drafting: A.S., D.N. Manuscript review and editing: A.S., A.C., D.N., C.C., F.H., M.S., J.W. Funding acquisition: C.C., F.H.

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Ethics Statement

We conducted this study in accordance with the Ufficio Tecnico Faunistico e Ittiofauna of the Provincia di Alessandria (authorisation numbers 65493 and DDAP2-939, dated November 11, 2021), as defined in Article 2 of Decree no. 26/2014 (implementation of Directive 2010/63/EU), and with Aree Protette Appennino Piemontese's agreement (authorisation number: 1072, dated February 15, 2022).

Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

The dataset is generated for this study. The data that support the findings of this study are available from the corresponding author.

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