Biol Invasions (2022) 24:1149–1173
https://doi.org/10.1007/s10530-021-02705-2

ORIGINAL PAPER

Tracking the early stages of an invasion with biotelemetry: behaviour of round goby (*Neogobius melanostomus*) in Canada's historic Rideau Canal

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Received: 18 July 2021 / Accepted: 3 December 2021 / Published online: 5 January 2022

Abstract The round goby (*Neogobius melanostomus*), native to the Black and Caspian Seas, is one of the most wide-ranging invasive fishes, having established in much of Europe and North America. In 2019, round goby were discovered to have colonized a central portion of the Rideau Canal, a 202 km historic waterway in Ontario, Canada. Round goby were found in low densities and had not been previously reported in any adjacent sections of the waterway, implying a newly-established source population. Passage through locks is the most likely means by which round goby can naturally disperse throughout the system, so modifying lock operations and infrastructure to minimize passages could reduce their spread. Additionally, understanding the range expansion and habitat preferences of pioneering individuals can help inform control efforts. We combined acoustic telemetry with hydraulic data to (1) characterize sex- and size-specific movements, (2) identify entry and exit pathways through a lock, and (3) assess dispersal rates and probability. We tracked 45 adult round goby downstream of Edmonds Lockstation during the navigation season from July to October, during which nine were detected inside the lock, with one fish successfully passing upstream. Most fish remained near the release site, though 26% of tagged individuals dispersed. The farthest distance a fish moved was 500 m (downstream) after 27 days, generating a maximum dispersal rate of 18.5 m/day. Although we lacked sufficient statistical power to detect size- or sex-specific movements, males were more commonly detected further from the release site. Our results suggest possible modifications to lock operations and

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1007/s10530-021-02705-2.

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infrastructure that managers could consider to reduce round goby expansion upstream from the invasion site.

Keywords Biological invasion · Connectivity · Conservation · Range expansion · Round gobies · Non-indigenous

Introduction

The round goby (*Neogobius melanostomus*), native to the Ponto-Caspian region of Europe, is a small (< 25 cm), benthic fish that is one of the most prominent aquatic invasive species in North America and Europe, with introduced populations in the Laurentian Great Lakes, the Baltic Sea, and several European rivers (Kornis et al. 2012; Brandner et al. 2015; Adrian-Kalchhauser et al. 2020). Rapid range expansion, explosive population growth, and life history trait plasticity have contributed to their success as an invader (Cerwenka et al. 2014; Brandner et al. 2015). Although numerous studies have reported the ecological and economic impacts of round goby invasions (see Balshine et al. 2005; Bergstrom and Mensinger 2009; Kornis et al. 2012; Oesterwind et al. 2017), few eradication or control attempts have been made (though see Dimond et al. 2010; Ojaveer et al. 2015; Dorenbosch et al. 2017). Biological invasions are complex and consist of different stages, including introduction, establishment, spread, and impact, each with an independent probability of success (Kolar and Lodge 2002); once a non-native species reaches the point of 'established' (is reproducing and forms a self-sustaining population; Gozlan et al. 2010), there is usually little hope for eradication. However, density and dispersion control, or functional eradication (suppressing invader populations below levels that cause unacceptable ecological effects; Green and Grosholz 2021), may be possible, especially if the invasion front is managed aggressively to stop further spread (Rytwinski et al. 2019).

In January 2019, 17 round goby were discovered near Edmonds Lockstation in the Rideau Canal Waterway, a National Historic Site of Canada, Canadian Heritage River, and UNESCO World Heritage Site, located in eastern Ontario, Canada (hereafter referred to as "Rideau Canal"; Parks Canada 2005). The Rideau Canal forms a 202 km continuous navigable route between Lake Ontario and the Ottawa River, and is interconnected by 47 locks and 24 lockstations, most of which have adjacent water-control dams (Fig. 1). When this waterway was constructed in the 1820s, three previously disconnected watersheds were connected (the Rideau River, Gananoque River, and Cataraqui River watersheds; Watson 2021). Located in the central region of the Rideau Canal, Newboro Lockstation represents the highest point of elevation (i.e., the "isthmus"; Fig. 1), with waters in the Rideau Watershed flowing downstream (northward) towards the Ottawa River and waters in the Cataraqui Watershed flowing downstream (southward) towards Lake Ontario. Large sections of the system at similar elevations (e.g., the Rideau Lakes) have negligible flows between adjacent reaches. Although connecting the watersheds offered new and potentially more suitable habitat to native species, it also enabled access to new geographic areas for non-native species and exotic pathogens (Leuven et al. 2009; Lin et al. 2020). The Rideau Canal is not unique in this sense; as of the late twentieth century, more than 63,000 km of canals exist worldwide (Revenga et al. 2000), forming convenient transport routes for supply transfer and facilitating countless biological invasions (Kelly et al. 2009). For example, the Welland Canal near Niagara Falls facilitated the destructive spread of invasive sea lamprey (*Petromyzon marinus*) from Lake Ontario to the upper Great Lakes (Sullivan et al. 2003; Siefkes 2017). Given that waterways with extensive anthropogenic modification (e.g., locks, dams) have been described as "invasion highways" for aquatic species (Leuven et al. 2009), it would be useful to better understand how infrastructure and/or operations in these systems could be refined to control the spread of invasive species.

To develop and implement a successful management strategy for invasive species, it is essential to understand how the species interacts with the environment, and the environment itself (i.e., how conducive the new environment is to that species). Biotelemetry is a valuable tool that can provide evidence and information on dispersal and movement patterns relevant to control efforts. Acoustic telemetry has been used to identify key habitats, activity times, and home ranges of invasive species worldwide, and can be highly relevant to management interventions which aim to control invasions (Lennox et al. 2016; Crossin et al. 2017). For example, Holbrook et al.

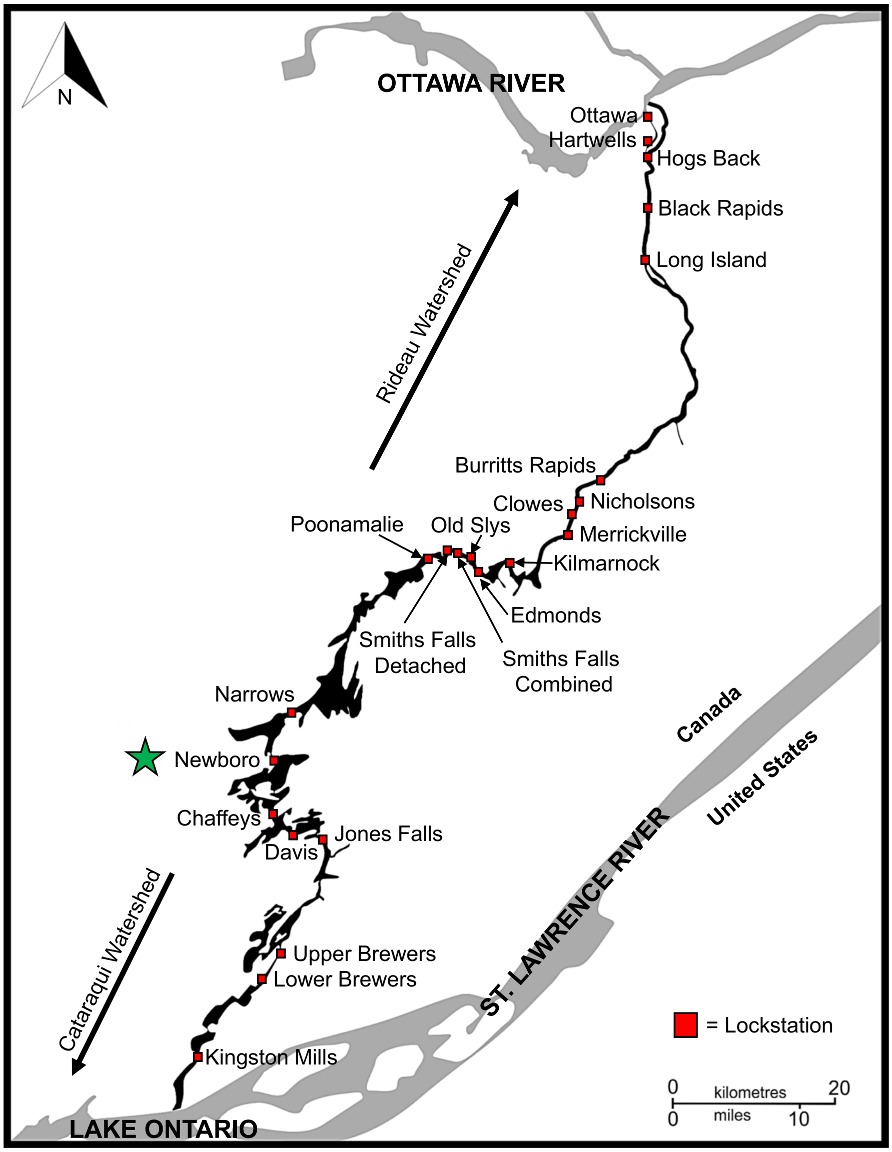

Fig. 1 Overview map of the historic Rideau Canal. The black channel represents the Rideau Canal Waterway, and the gray channels represent hydrologically-connected waters (Lake Ontario and the St. Lawrence River in the south; the Ottawa River in the north). Red boxes indicate lockstations that interconnect the system. Newboro Lockstation, indicated by the green star, is the "isthmus," representing the highest elevation on the Rideau Canal and delineates the Rideau Watershed (flowing north) and the Cataraqui Watershed (flowing south). Lake Ontario and the St. Lawrence River act as a natural border between Canada and the United States. Note that this map does not include the lockstation that connects the main waterway to the Tay Canal. Although round goby are present throughout Lake Ontario and the St. Lawrence River, they were unknown to have invaded the Rideau Canal until 17 fish were discovered near Edmonds Lockstation in January 2019. Our acoustic telemetry array ($N = 29$) focused on an 8.7 km portion of the Rideau Canal between Old Slys Lockstation and Kilmarnock Lockstation

(2014) used acoustic telemetry to evaluate if the lock and dam in Cheboygan River, Michigan, a tributary of Lake Huron, serves as a barrier to upstream passage of invasive sea lamprey. Although no tagged lamprey were detected above the Cheboygan Dam, they estimated that 0–2% of the untagged population could have escaped upstream, most likely exploiting the vessel lock and passing upstream during lock operation (Holbrook et al. 2014). Indeed, conservation actions are less likely to be effective when animal movements are not considered (e.g., the scale or timing of movements; Allen and Singh 2016).

Numerous efforts have been made to evaluate movement patterns of round goby, but only one published study has used telemetry tracking to quantify their movements (see Christoffersen et al. (2019) who examined diel and seasonal patterns in a Baltic Sea estuary). Although researchers have conducted field experiments to provide information on round goby dispersal patterns (e.g., see Lynch and Mensinger 2012; Marentette et al. 2011, 2012; Šlapanský et al. 2020), the mark-recapture methods used do not provide fine-scale, round-the-clock movement data like those that telemetry does. Collectively, those articles offer a deeper understanding of round goby spatial ecology, though it would be inappropriate to apply results from those studies to the Rideau Canal population given individual variability and incomparable regions and ecotypes. As such, the main goal of this study was to characterize the establishment and spread of the recent biological invasion of round goby in the Rideau Canal, and specifically (1) to evaluate the passability of locks as potential upstream dispersal pathways, (2) to characterize round goby space use and overall dispersal, and (3) as the first researchers to acoustically tag round goby this small, to identify potential impacts of acoustic tagging.

Materials and methods

Study area

This study took place in an 8.7 km section of the Rideau Canal spanning from Old Slys Lockstation (N 44°53.590' W 76°00.250') to Kilmarnock Lockstation (N 44°53.075' W 75°55.825') (Fig. 1; Online Resource 1, Fig. S1). In this article, a "lock" refers to a chamber with gates (i.e., doors) at both ends that allows water to be let in or let out to raise or lower a vessel from one water elevation to another (i.e., to move upstream or downstream), whereas a "lockstation" describes an entire site, including land and associated buildings, the lock(s), the water-control dam and weir, and any other navigation or water-management structures. Though many lockstations in the Rideau Canal are single locks (i.e., only one lock chamber), several are composed of multiple locks in close proximity, ranging from two to eight locks in flight (i.e., connected to each other by gates). Construction of the Rideau Canal was completed in 1832, primarily for commercial shipping and national Canadian defence (Forrest et al. 2002), to provide a direct route from Lake Ontario at Kingston, Ontario to the Ottawa River at Ottawa, Ontario. Today, it is mostly used for recreational purposes and is maintained by the federal agency Parks Canada primarily for navigation and to preserve commemorative integrity of the waterway (Acres 1994; Parks Canada 2005; Bergman et al. 2021). Many shorelines in the area are stabilized with rocky riprap, though several regions are stabilized instead by shoreline vegetation or concrete vertical retaining walls (RVCA 2019). Lakes, rivers, and constructed channels in the study area have bottom substrate consisting of clay-bed, sand, rocks, gravel, and pebbles, with some areas being heavily vegetated. The Rideau Canal is a biodiverse freshwater system and has been described as having one of the most diverse fish assemblages (107 documented fish species; Coad 2011) in Canada (Poulin et al. 2001; Parks Canada 2005). This system supports both recreationally important gamefish, like largemouth bass (*Micropterus salmoides*) and muskellunge (*Esox masquinongy*), as well as at-risk species like bridle shiner (*Notropis bifrenatus*; special concern) (Poulin et al. 2001; COSEWIC 2020). A navigation channel along the entire waterway is maintained (typically $\geq$ 1.5 m) during the navigation season for boaters to travel safely. Aquatic vegetation that impedes boaters is removed within the navigation route, though areas outside of the deeper main channel are shallow ($\sim$ 1–2 m deep) with large expanses of aquatic vegetation and riverine wetlands. In 2019, the navigation season began 17 May and ended 14 October.

Edmonds Lockstation (N 44°52.650' W 75°59.015') consists of a 40.8-m-long and 10.5-m-wide lock (see Fig. 2A and 2C for an aerial view of the lock chamber and downstream gates, respectively, and Fig. 3 for a 3-D view). When the downstream and upstream gates are open, the average depth inside the lock chamber is 2.2 m and 5.1 m, respectively. Edmonds Lockstation has a 167-m-long and 4.1-m-high stone arch dam consisting of a 96 m overflow stone weir and a 7.5 m long waste-weir of stacked logs (Wanless 1997). The lock is situated at the east end of a 150 m excavated (navigation) channel. Edmonds Dam spans the width of the Rideau River, creating a 2.7 km slackwater section to the upstream double-flight lockstation, Old Slys. The section from Edmonds Lockstation downstream to Kilmarnock Lockstation is also slackwater (for information on slackwater technology, see https://www.pc.gc.ca/en/docs/r/on/rideau/whl-lhm/chap3/chap3C), spanning 6.0 km and includes extensive wetlands and a lacustrine area of open water with heavy vegetation (Online Resource 1, Fig. S1).

There are several different ways in which fish can enter Edmonds Lock. First, when the upstream or downstream lock gates are open, a 10.5-m-wide channel becomes available for fish to use. Second, on the downstream gates, there are four sluice valves (two on each gate) near the bottom which release water from the lock chamber via a swing-type plate (Fig. 3B). When opened, each valve has two rectangular areas 0.46-m-high and 1.52-m-wide that fish can swim through. Third, there are two sluice tunnels on the upstream end of the lock which are used to fill the chamber (Fig. 3C). The sluice tunnels are approximately 1.4-m-high, 0.9-m-wide, and 10.5-m-long (Government of Canada 1987). The tunnel entrance is divided into four rectangular areas for fish to enter, ranging in height from 0.19 to 0.37 m with a width of 0.85 m. Hereafter, we refer to downstream gate valves as "valves" and upstream sluice tunnels as "tunnels." Depths in the areas surrounding Edmonds Lockstation are relatively shallow during average summer flows, mostly 1–2.5 m deep, with a deeper 4.0 m pool located upstream of the dam (Online Resource 1, Fig. S2). During non-operational hours (i.e., night),

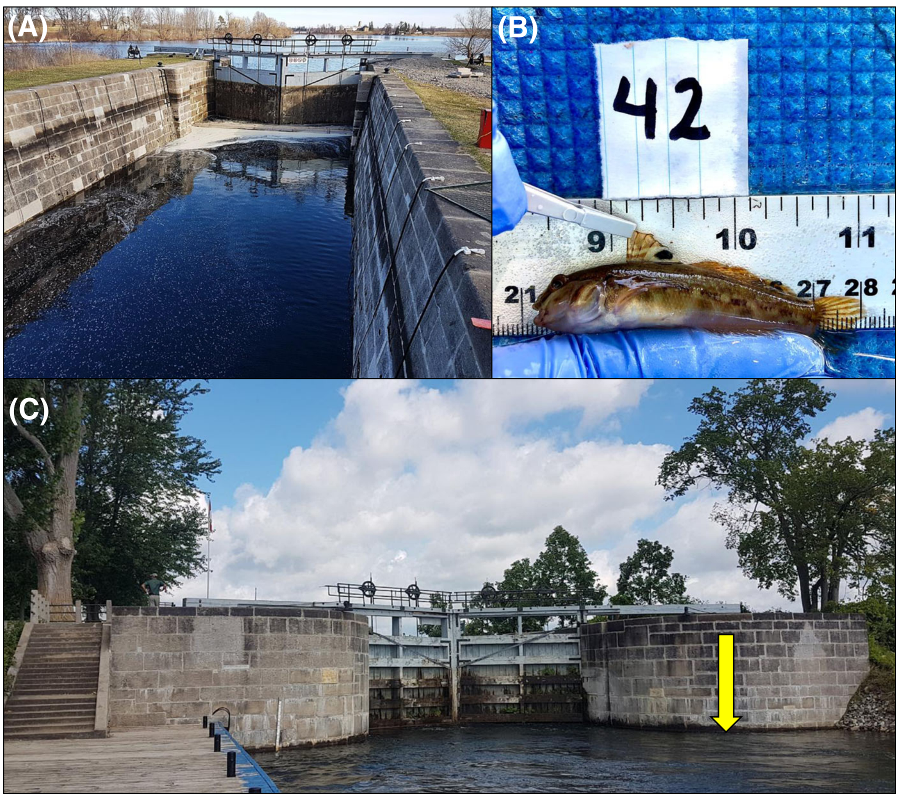

Fig. 2 Images of the study site, Edmonds Lock, Smiths Falls, Ontario, where round goby were first discovered in the Rideau Canal. **A** Image of the lock chamber as water levels are being lowered. The gates in the image are the downstream gates. Note that most locks in the Rideau Canal, including Edmonds, are still manually operated by hand. **B** Each round goby captured and acoustically tagged was photographed to confirm species. **C** View of the Edmonds Lock downstream gates. The yellow arrow indicates the site-of-release station placed immediately outside and downstream of the chamber to determine if and/or when tagged fish entered and exited the lock, or dispersed from the area. All tagged goby were released at this station. Image credits: (**A**) and (**C**) taken by Kate Neigel, and (**B**) taken by Jordanna Bergman

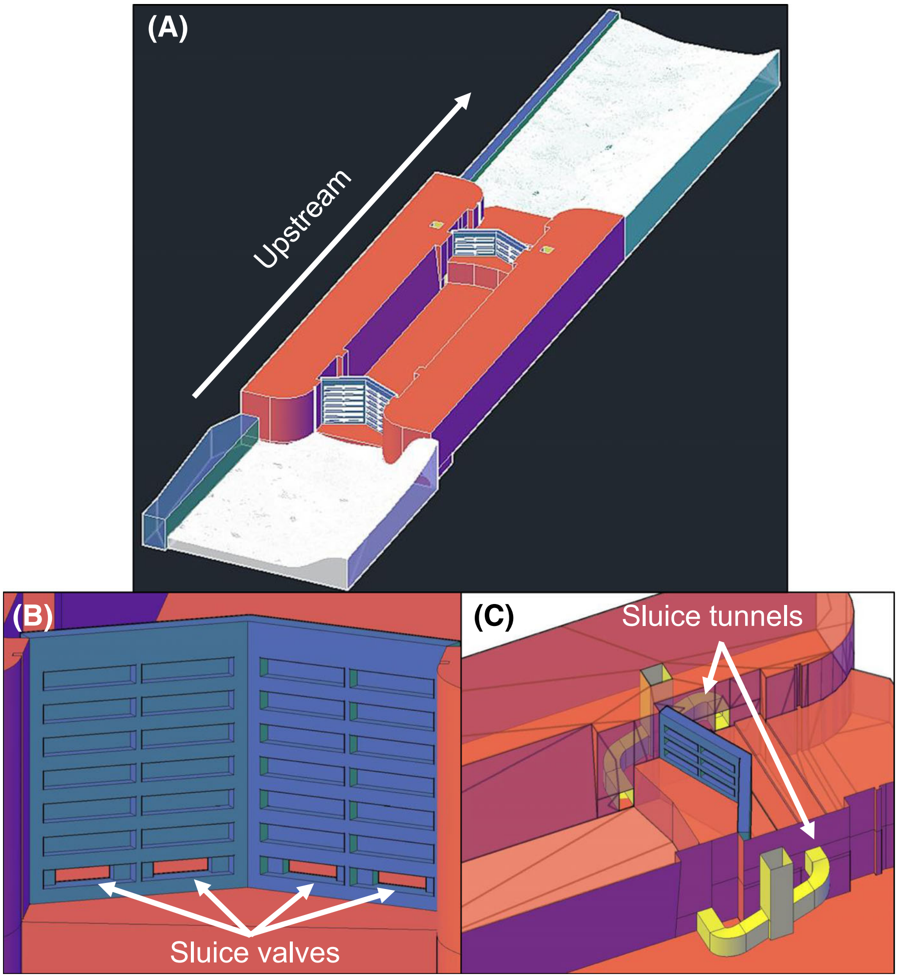

Fig. 3 3-D images of Edmonds Lock chamber and channel. **A** A full view of Edmonds Lock and its navigation channel. Note that the upstream gates are at a higher elevation, and therefore shorter, compared to the downstream gates. The Edmonds Lock chamber ranges from 10.06 to 11.58-m-wide and is 41-m-long. Water depth in the lock chamber when downstream and upstream gates are open is 2.2 m and 5.1 m, respectively. When water levels are low (i.e., 2.2 m), the platform (i.e., gate sill) on the upstream side of the lock is exposed. In respect to upstream dispersal, when water levels are low, round goby cannot pass upstream as they would be exposed to air. **B** A 3-D image of the downstream-lock gates. To empty the lock chamber, lockmasters manually open these valves to release water. These valves are left open during non-operational hours (i.e., night) to maintain low-water levels in the chamber for safety purposes and to minimize unnecessary pressure on infrastructure. Telemetry results indicate these valves provide a path for round goby to enter and exit the lock, even when the downstream gates are closed. **C** A 3-D view of the upstream portion of Edmonds Lock. The 0.9-m-wide and 1.4-m-high yellow sluice tunnels are used to manually draw water into the lock chamber for filling. Lockmasters close the intake valves for the tunnels when not in use. These tunnels may also serve as a path for round goby to move upstream and exit the chamber (provided the lock is full, not operating, and the valves have been left open) or enter the lock chamber when water is being pulled in during filling. Photo credits: all images created and provided by Kate Neigel

water levels in the lock chamber are lowered to minimum depth (i.e., 2.2 m) for safety purposes and to relieve pressure on infrastructure. During non-operational hours, lockmasters leave 1–2 valves open on the western downstream gate to ensure water levels remain low (Parks Canada, personal communication).

Acoustic tagging

As this is a new invasion, we expected round goby densities to potentially be low; thus, snorkel and free diving surveys were conducted downstream of Edmonds Lockstation to determine where sampling efforts should be focused. We surveyed the lock channel and the area within ~ 250 m downstream of the dam, observing round goby only near the dam and along the far eastern shoreline. Round goby were discovered at Edmonds Lockstation only six months prior and this area is one of the few regions in the reach with rocky substrate that round goby prefer (see below). Based on these observations and our surveys, we assumed that the round goby population was likely to still be close to the dam and we therefore did not conduct additional snorkel surveys throughout the entire reach. Further, we chose to not continue extensive surveys throughout the full 8.7 km study system in order to deploy tags and begin tracking round goby movements swiftly. Fish sampling occurred from 9 to 18 July 2019 during the day between 0900 and 1700. Round goby were collected using a backpack electrofisher (LR-24 electrofisher, Smith Root, Vancouver, Washington, United States). Electrofishing by slow wading upstream along the right bank, as well as immediately downstream, of Edmonds Dam (denoted by areas within the black dashed lines on Fig. 4) was the most effective sampling method for catching a range of sizes of round goby inhabiting the littoral zone (mostly in rocky areas). Several studies have shown round goby prefer hard substrates for spawning and feeding (Charlebois et al. 1997; Ray and Corkum 2001; Bhagat et al. 2015) and the interstitial spaces created by rocks provide refuge from predation (Jude and DeBoe 1996). Other methods (e.g., beach seining, traps, angling) were not used due to inappropriate habitat conditions and low efficiency, and electrofishing nearshore habitats has previously been shown to be a reliable method for sampling round goby (Šlapanský et al. 2020). Due to bathymetric gradients, sampling was restricted to within 3 m of the water's edge.

All captured round goby were immediately placed in a 19 L plastic bucket filled with fresh river water and brought to shore. Body measurements taken, including total length (TL), standard length (SL), head width (HW), body width (BW), and genital papilla length (GPL, measured with calipers), were measured to the nearest 1 mm and 0.5 mm for GPL. Each round goby was photographed to confirm species identification (e.g., Fig. 2B). Sex was determined by visually examining the urogenital papillae, located between the base of the anal fin and the anus, which in females is broad and blunt and in males is long and triangular (Charlebois et al. 1997). The smallest round goby captured was 52 mm TL; according to size-at-maturity literature values for round goby in North America whereby individuals > 50 mm TL are adults (Phillips et al. 2003; Lynch and Mensinger 2012; Blair et al. 2019), all individuals were classified as such. To minimize potential negative impacts of tag burden, only individuals ≥ 65 mm TL were implanted with acoustic transmitters (hereafter, 'tags'), with the exception of one round goby that was 61 mm TL. Individuals < 65 mm TL captured were donated to the Canadian Museum of Nature as voucher specimens. Thus, we refer to two separate groups of round goby for morphological analysis: the "tagged population" refers only to acoustically tagged individuals, and the "total population" refers to all round goby captured. Mass measurements were not taken in the field; they were instead extrapolated from a least-squares linear regression model using length–weight data ($N = 1724$) from a population of round goby in Hamilton Harbour, Ontario, Canada ($R^2 = 0.96$; dataset provided by S. Balshine).

Forty-five round goby were implanted with a 'small' ($N = 26$) or 'large' ($N = 19$) sterilised (betadine) mini-acoustic Lotek Wireless Juvenile Salmon Acoustic Telemetry System (JSAT) tag in the coelomic cavity (small: L-AMT-1.416, 0.28 g in air, $10.7 \times 5.4 \times 3.1$ mm, expected battery life = 87 days; large: L-AMT-1.421, 0.32 g in air, $11.1 \times 5.5 \times 3.7$ mm, expected battery life = 131 days). Tag type (i.e., large versus small) was relatively evenly distributed across sexes, with males ($N = 18$) implanted with nine large tags and nine small tags, females ($N = 22$) implanted with nine large tags and 13 small tags, and the smaller individuals of unknown sex ($N = 3$) implanted with small tags. The tags used were the smallest commercially available acoustic transmitters at the time; because of their small size, we inserted them using methods similar to PIT tagging. Fish were individually transferred to a foam-lined V-tray filled with fresh river water and placed supine such that the head and gills were submerged in water but the incision site was left dry. No anesthetic was needed given that fish remained immobilized while supine and because of the speed and simplicity of the procedure. Tags were inserted through a lateral-ventral incision (≤ 5 mm) posterior to the pectoral fin using a sterilized No. 21 scalpel. Sutures have been considered unnecessary for small (< 1 cm) incisions

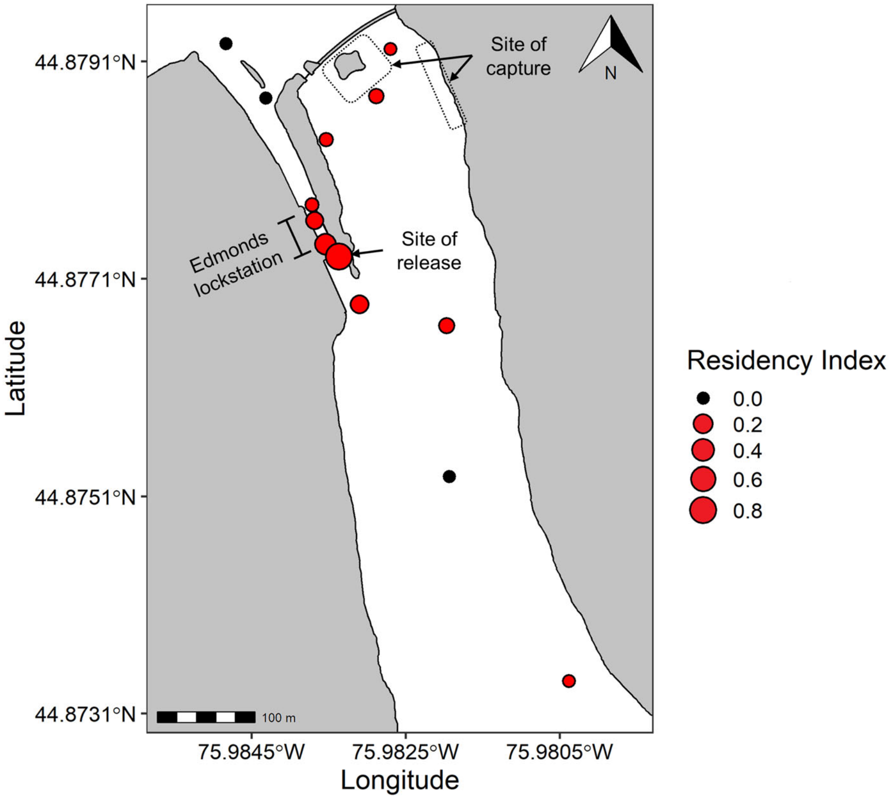

Fig. 4 Round goby Residency Index (RI) by acoustic receiver station. Each circle represents mean RI at that station for all tagged round goby across the entire monitoring period 10 July 2019 to 12 October 2019. Red circles indicate at least one round goby was detected at that station; black circles indicate no fish were detected there. Circles are graduated such that larger circles represent more time and/or more individuals at that location. Note that the size of the site-of-release station is inflated as all tagged round goby were translocated from the site of capture (denoted by areas within the black dashed lines) and released there. Receivers were placed immediately (5 m) outside Edmonds Lock on the upstream (more north) and downstream (more south) sides to detect if and when fish entered and exited the lock. Four receivers were placed inside the lock with one in each corner. To determine if fish entered the lock chamber, the lock-chamber receivers on the upstream ($N = 2$) and downstream ($N = 2$) ends were grouped into distinct stations, respectively, such that there are two lock-chamber stations. Only one individual was detected at the most southern station on the map, at 500 m from the site of release

in fish tissue (Baras and Jeandrain 1998; Shelton and Mims 2003; Acolas et al. 2007; Raoult et al. 2012), yet, from an ethical perspective, closing the wound after tag insertion may be important in terms of reducing infection (Hegna et al., 2019). Thus, 19 fish were randomly selected to have cyanoacrylate adhesive applied to their incision. Of the males tagged, 66% had glue applied to their incision. In the field, glue was applied randomly to every second or third fish, resulting in a bias of more males having glue applied to their incisions. Glue was applied to incisions on 50% of tagged females (equal proportion of females with and without glue applied to their incisions). One of the three individuals of unknown sex had glue applied to its incision. The tag:body-mass ratio (i.e., tag burden) was on average 5.3% (range: 0.8–10.4%). The highest tag burden of 10.4% is on the upper end for electronic tagging of fish, however there is a growing body of literature suggesting there is no universal "rule" for tag burden, and that some fish species do not exhibit significant impairments when tagged with devices as much as 8–12% of body mass (Brown et al. 1999; Lacroix et al. 2004; Jepsen et al. 2005; Cooke et al. 2011). Tag burden and the application of glue to the incision was recorded to evaluate potential effects of the tagging procedure on apparent survival and short-term movements. All tagged fish were marked (superficially injected) with non-toxic, pink acrylic paint beneath the dorsal fin in case of recapture (O'Brien and Dunn 2018). The entire procedure took 2–4 min. Fish were monitored for post-surgical behaviour changes (e.g., equilibrium imbalance, change in ventilation rate, lack of movement when gently prodded; Tsitrin et al. 2020) in a recovery bucket with fresh river water for a minimum of 30 min post tagging and released thereafter to minimize potential deleterious effects from prolonged confinement (Jepsen et al. 2002). No fish showed any apparent deleterious effects from surgery. We released all acoustically tagged round goby immediately downstream of Edmonds Lock over the site-of-release receiver (Fig. 2C) to (1) ensure we could detect at least initial tag transmissions and have a single point from which to track movements (i.e., standardizing movements across depth and habitat), (2) evaluate upstream movements into and/or through Edmonds Lock, and (3) determine if round goby have a propensity to return to their site of capture near the dam (i.e., "home"). Although round goby can be habitat generalists (Henseler et al. 2020), as mentioned above literature indicates they prefer rocky, riprap habitat which in our study area is common in both the lock channel and near the dam (J.N. Bergman, personal observations).

Acoustic telemetry array

Twenty-nine acoustic receivers (Lotek Wireless, WHS 4250, 416.7 kHz) were deployed in strategic locations to track tagged fish movements. Receivers were stationed inside the lock chamber and immediately outside (5 m) on the upstream and downstream ends of Edmonds Lock to detect space use and successful passage events, and evenly throughout the reaches upstream and downstream of Edmonds Lock to examine dispersal capacity and overall movements (Online Resource 1, Fig. S1). A higher density of receivers was placed downstream of Edmonds Dam (i.e., the site of capture) to investigate potential homing capability in round goby. Receivers were deployed 17 May 2019 and collected 25 October 2019 and were anchored to the bottom with the hydrophone positioned $\sim$ 0.6 m above the substrate. Receiver locations were recorded using a handheld GPS unit. Range and detection efficiency tests of our receivers were conducted post hoc in June 2020. For detailed information and results for range and detection efficiency testing, see Online Resource 1: Table S1, Fig. S3, and Fig. S4.

Hydraulic survey and processing

Hydraulic surveying and processing inside Edmonds Lock was conducted to evaluate how fish interact with lock infrastructure and in the surrounding area to determine potential effects of velocities on fish movements. Onset HOBO U20-001–01 Water Level Loggers (Bourne, Massachusetts, United States) were installed adjacent to three receivers on 10 May 2019 to record temperature and pressure: one 120 m upstream Edmonds Lock, one 50 m downstream of Edmonds Lock, and one inside the Edmonds Lock chamber in a downstream corner. An additional logger was installed on shore to record barometric pressure and to calculate depth of the other loggers. A hydraulic survey was conducted in the local area surrounding Edmonds Lockstation extending from approximately 200 m upstream to 100 m downstream. Bathymetries and velocities were surveyed over three days from 20–27 August 2019 using a remote-control Teledyne Marine Q-Boat 1800 (Poway, California, United States) equipped with SonTek M9 RiverSurveyor (San Diego, California, United States) acoustic Doppler current profiler (aDcp). Bathymetry and velocity data were processed using MATLAB code developed by Rennie and Church (2010). Ordinary kriging interpolation was applied to the processed bathymetric plus topographical data received from Parks Canada, and u- and v-depth-averaged velocity components to determine bathymetry and depth-averaged velocity vectors for the reach. For a more detailed explanation of our hydraulic survey and data processing, see Online Resource 2.

To evaluate the path by which round goby may enter or exit the lock chamber, we investigated lock operations and chamber water levels. By determining the rate at which the lock was filled, we could deduce if a boat was inside the chamber: when a boat is present inside of the lock, the lock is filled slowly (with the operators' intent to prevent vessel damage due to turbulence). As such, if the lock was filled slowly, we assumed the downstream gates were opened for at least a few minutes prior to allow a boat to enter, and for a few minutes the upstream gates would be open post-filling to allow a boat to exit. Lock fill rate was therefore used to help uncover potential routes of entry and exit (e.g., through valves versus through open gates). Drain rate, conversely, could be fast or slow, depending more so on how lockmasters operated the lock (e.g., if only one lockmaster was present, they may have opened 1–2 valves instead of all 4), and not if a boat was present (Parks Canada, personal communication).

Data analysis

Raw detection filtering

Telemetry data were processed and statistical analyses were conducted using R version 3.6.2 (R Core Team 2019). Conducting acoustic telemetry research in close proximity to "noisy" structures, like navigation locks and dams, can result in a high number of false positive detections; thus, several filters were employed to identify and remove likely false positives. We identified and removed detections from tag IDs that were not in round goby (i.e., tag IDs implanted in other species in the system; 31,362,391 detections removed; remaining "true" detections: 456,367). Any known tag ID detections recorded by receivers that occurred before that tag ID was deployed in the system were also removed (5900 detections removed; remaining "true" detections: 450,467). We used a 'min lag' filter from the GLATOS package (Holbrook et al. 2019; Algera et al. 2020; Tuononen et al. 2020), which uses an a priori determined number of detections within a specified timeframe, to identify potential false positive detections. For our study, we required a minimum of two detections to occur on a given receiver within a 10 min period for either detection to be considered "true" (22,611 detections removed; remaining "true" detections: 427,856). We then applied an "interval method" filter (e.g., Algera et al. 2020) whereby we used the programmed JSAT transmission interval (here, 20 s between signal transmissions) to identify false detections. The first transmitted ID detection was considered "true," and subsequent detections outside the 20 s interval were removed from the dataset (66,233 detections removed; remaining "true" detections: 361,623). Signal power of each detection was also considered. Power readings reflect the strength of the detected signal, ranging from 0 to 1500 dBm, and can be affected by a variety of factors like distance between receiver and tag, tag orientation, and ambient environment; false positive detections generated by ambient noise typically have weak power values. We generated and visually inspected a histogram of detection power levels and based on observations of outliers we assumed that detections with power levels less than 20 dBm were likely false; these detections were removed (8682 detections removed; remaining "true" detections: 352,941). Finally, we applied a detection event filter to the dataset (Holbrook et al. 2019). The detection event filter groups individual detections into discrete events, defined by movements between receivers or receiver groups (i.e., stations) and sequential detections at the same station separated by a predefined time frame. Because of their close proximity (9 m), we grouped the two receivers on the upstream end and the two receivers on the downstream end of the lock chamber together, resulting in two distinct lock chamber stations ('upstream lock chamber receivers' and 'downstream lock chamber receivers'). All other receivers were considered unique stations. Detections that occurred in sequence with gaps of < 1 h between detections at the same station were considered a detection event; if a full hour passed between sequential detections, the subsequent detection was considered to be the start of a new detection event (352,941 raw detections were reduced to 68,083 detection events). Individual fish abacus plots (Online Resource 3) were visually inspected to verify that detection event timestamps and locations were logically and biologically plausible. To eliminate implausible detections (e.g., fish quickly moving large distances, or moving back and forth across the dam or lock), we filtered out detection events with ≤ 3 raw detections. After applying this requirement to the detection event filter, we carefully inspected the dataset and found all events appeared plausible, resulting in a final dataset of 14,468 detection events from 43 round goby (two fish were not detected post-filtering). Although detection range and efficiencies were evaluated, receiver detection efficiencies were low (Online Resource 1, Table S1). Consequently, detection efficiency and range testing results were not formally integrated into our data analyses; instead, we use them descriptively to provide context for our interpretation.

To evaluate round goby movements inside the lock chamber, detections were filtered slightly differently. The same initial filtering process was still applied (i.e., interval method, min lag filter, minimum power signal requirement), however the detection event filter was altered. Although beacon devices (acoustic tags inside the receiver that emit a signal) were activated on the four lock chamber receivers for range and detection efficiency testing, the testing failed, likely as a result of high ambient noise inside the lock (Lotek Wireless, personal communication). Thus, to determine a finer resolution of round goby movements inside the lock, we grouped the four lock chamber receivers together into a single station. When multiple receivers are grouped into a station, the detection event filter calculates a single, average position based on the detections heard during the event, offering a way to visually assess where and when round goby spent their time in and near the lock. Abacus plots (Online Resource 3) indicated that detection ranges of the downstream-lock-chamber receivers and the receiver located immediately outside the lock on the downstream side (i.e., the site-of-release receiver) appeared to overlap; thus, the site-of-release receiver was also included into the station for lock-movement analysis. The event filter does not triangulate fish positions; instead, it produces a relative sense of where fish were detected most among those receivers, comparable to a "centre of activity" evaluation for fish movements near and inside the lock chamber. This analysis assumes roughly similar detection range and efficiency for each of the four lock receivers. The receiver immediately outside the lock on the upstream side was left separate as it was at a higher elevation (+ 3 m) and did not appear to overlap in detection range with the receivers inside the lock. The final lock detection dataset included 743 detection events.

Morphology and movement type analysis

Body measurements (TL, SL, BW, HW, GPL) were evaluated for normality; these variables did not meet assumptions of equal variance and normality (as assessed using Levene's Test for Equality of Variances) so we evaluated them using permutation tests with 100,000 permutations. To evaluate potential drivers of movements, we used two binomial logistic regression models. The logistic regression models were designed to evaluate the potential effects of body size (TL), sex (categorical variable), if glue was applied to the incision (yes or no, categorical variable), and tag burden on round goby (1) dispersal away from the site of release (i.e., movement type analysis) and (2) entry into the lock chamber (i.e., lock chamber entry and passage analysis). We chose to use logistic regression over other techniques (e.g., linear regression) as our measures of movements were binary; individuals either dispersed away from the site of release (1, designated "roamer") or remained (0, designated "resident"), and either entered the lock (1) or did not (0). Interactions were not included due to insufficient statistical power. An alpha level of 0.05 was set for analyses.

To map detection events, round goby Residency Index (RI) was calculated by dividing the total number of days detected at each station by the total number of days the individual fish was detected anywhere in the array (using the 'Kessel method' in the GLATOS package; https://rdrr.io/github/jsta/glatos/man/residence_index.html). We used RI as it reduces the potential bias of a large number of detections at a given station generated by only a few individuals (Kessel et al. 2016). RI was not analyzed for movement or dispersal patterns as round goby were translocated to the site-of-release station from their site of capture, and sample sizes were low at most stations. Because the tags used have a maximum expected battery life of 131 and 87 days—a relatively short amount of time to assess fish movement patterns—for large and small tags, respectively, we relocated tagged individuals to the site-of-release station to give us the best chance at answering key research questions. Additionally, we know of only one other research group who has successfully tracked round goby using acoustic telemetry (Christofferson et al. 2019), and those fish were ~ 70% larger (TL) compared to the round goby captured in this study.

Results

Morphology and sex ratio

Total population

In total, 58 round goby were captured and measured (32 females, 22 males, and four individuals of unknown sex). The sex ratio of the total population (female to male) was 1.45:1. The four individuals of unknown sex (genital papilla too small to identify sex) were excluded from size and movement analyses. Males were significantly longer (on average 7.61 mm longer; TL: $P = 0.04$; SL: $P = 0.04$) and heavier (on average 2.75 g heavier; mass: $P = 0.03$) than females. No statistical differences were found between males and females for head width ($P = 0.09$), body width ($P = 0.24$), or genital papilla length ($P = 1$). Detailed information of sex-specific size measurements can be found in Online Resource 1, Table S2.

Tagged population

Forty-five round goby were acoustically tagged and released at the site-of-release station (Fig. 2C). This included 22 females, 18 males, and three individuals of unknown sex. The sex ratio of the tagged population (female to male) was 1.22:1. The three individuals of unknown sex were excluded from size and movement analyses. Overall, males appeared to be larger than females, though no statistical significance was found when comparing total length ($P = 0.08$), standard length ($P = 0.10$), mass ($P = 0.10$), head width ($P = 0.15$), body width ($P = 0.34$), and genital papilla length ($P = 0.72$). Detailed information of sex-specific size measurements for acoustically tagged round goby can be found in Online Resource 1, Table S3.

Hydraulic survey

Water levels were monitored in the lock chamber to determine the timing of lockages and the number of opportunities fish had to move upstream (to overlay with detection data). We define a "lockage" as an event where a vessel entered the lock chamber and water levels were raised or lowered to allow upstream or downstream passage, respectfully. During the study period, upstream and downstream water levels varied by 8 cm and waste-weir operation remained constant. Average water temperatures in July (9–31 July), August, September, and October (1–11 October) were 26.3 °C, 23.9 °C, 19.4 °C, and 14.2 °C, respectively. A total of 603 complete lockage cycles and 19 partial lock cycles (where the lock only filled or emptied partially) occurred during the study period, with a mean of 6.2 cycles/day. On average, there were 8.5 daily lockage cycles in July (9–31 July), 8.6 in August, 3.7 in September, and 2.2 in October (1–11 October). Velocities upstream of Edmonds Lockstation ranged from 0.0 to 0.15 m/s, increasing near the waste-weir, and velocities downstream of Edmonds Lockstation ranged from 0.0 to 0.4 m/s. The peak velocity in the study reach was 0.6 m/s immediately downstream of the waste-weir (Fig. 5). Depth-averaged velocities measured inside the lock chamber were measured to be up to 1.5 m/s during lockages but < 0.05 m/s otherwise. We found that following a lock fill, the lock chamber remained full (with upstream gates open) for an average of 34 min, and up to 244 min. Based on known swimming speeds, round goby would only be restricted by velocities in the area immediately downstream of the waste-weir and within and near the lock during operation (Tierney et al. 2011: sprint = 0.66 ± 0.02 m/s, prolonged = 0.36 ± 0.01 m/s; Egger et al. 2020: sprint = 0.43 ± 0.14 m/s, prolonged = 0.54 ± 0.10 m/s [note that sprint values were lower than prolonged values likely due to forced swimming or substrate holding during sprint tests versus volitional swimming during prolonged tests]).

Movement analysis

Over the duration of the study, 96% (43/45) of the fish tagged were detected in the receiver array. The total time detected for each fish ranged between three hours to 88 days, with an average detection time of 16 days. More than half (53%) of the tagged fish were detected for fewer than seven days (Online Resource 1, Fig. S5). Tag burden did not differ significantly between males and females ($P = 0.14$). Statistical output for logistic regression models can be viewed in Online Resource 1, Table S4.

Roamer versus resident round goby (movement type analysis)

We conducted a series of binomial logistic model analyses to examine which variables might predict movement type (i.e., resident or roamer) in our tagged round goby. Fish size (TL), tag burden, glue application to incision, and sex did not have an obvious effect on movement type. Round goby that were detected only at the release site, the receiver 50 m downstream in the lock channel, or inside the lock were classified as "resident"; most of our tagged round goby (74%) were classified as such and remained near the release site. A total of 26% (11/43) of tagged fish left the lock channel altogether (i.e., roamers) and were detected either back at their original site of capture ($N = 4$) or in the main Rideau River channel ($N = 7$) (Fig. 4). Roamers included a fairly even number of both sexes (six males, five females), though three of the four fish that returned to the site of capture were male. Seventy-three percent of roamers did not have glue applied to their incision. The farthest (from the release site) a

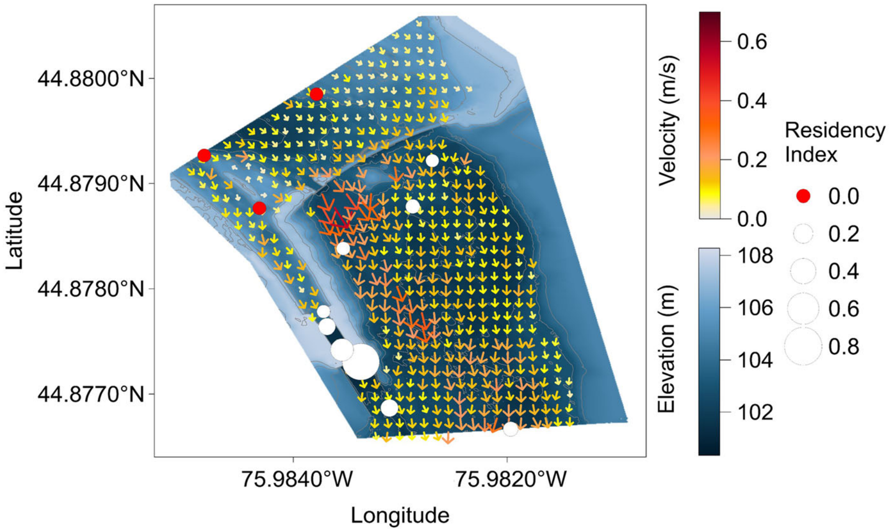

Fig. 5 Typical water velocity flow field when Edmonds Lock is not in operation, with the average water level (elevation) upstream and downstream of Edmonds Lock and Dam at 106.48 m and 103.61 m, respectively, during the study period. Arrows indicate the direction and velocity (m/s) of water flow, with arrows size- and color-graduated such that the larger and 'redder' the arrow is, the higher the velocity. Highest flows can be seen beneath the Edmonds Dam near the site of capture. Residency Index (see Fig. 4) has been overlaid to show fish residency at receiver stations in combination with water velocities

round goby was detected during the study period was ~ 500 m downstream, 27 days after being tagged and released. The mean body size (TL) of roamers versus residents was almost equal at 76.73 mm and 76.84 mm, respectively. Mean tag burden of roamers versus residents was also similar at 5.05% and 5.38%, respectively. See Online Resource 1, Table S5 for detailed information on where individual round goby were detected.

Lock chamber entry and passage analysis

Nine of the 43 tagged round goby (21%) entered the lock chamber, including three males, five females, and one of unknown sex (Fig. 6; Online Resource 1, Table S5). Because it appeared the downstream lock chamber receivers overlapped in detection range with the site-of-release receiver, we required fish be detected on upstream lock chamber receivers to be considered to have truly entered the lock (see abacus plots: Online Resource 3; Fig. 6). Though none of the predictors we examined (TL, sex, tag burden, application of glue to surgical incision) appeared to be linked to whether round goby entered the lock, larger fish had a tendency to enter the lock, though this relationship was not significant ($P = 0.07$). Four individuals entered the lock and remained there until they stopped being detected (i.e., tag battery died); five round goby entered and exited the lock. Residence time in the lock varied greatly, ranging from 30 min to 87 days. By comparing detection data to water-level data in the lock chamber, and taking into account hours of operation, we were able to determine potential pathway(s) of entry and exit (Online Resource 4). Five fish entered the lock chamber during non-operational hours through open downstream-gate valves. Four fish entered the chamber during operational hours: one fish entered while downstream gates were open to allow entry to a vessel for an upstream lockage, one fish entered while gates were closed through downstream valves, and for two fish it was unclear if they entered via downstream-gate valves or when gates were opened for a lockage. Of the five fish that exited the lock after being detected inside the chamber, three exited during non-operational hours via open downstream valves, and for the other two fish it was unclear if they swam out by their own means through open valves or if they were flushed out when the lock was being drained. Only one round goby was detected upstream of the lock (fish FCA9). This 82 mm female, with a large-size tag and no glue applied to the surgical tagging site, was detected on the

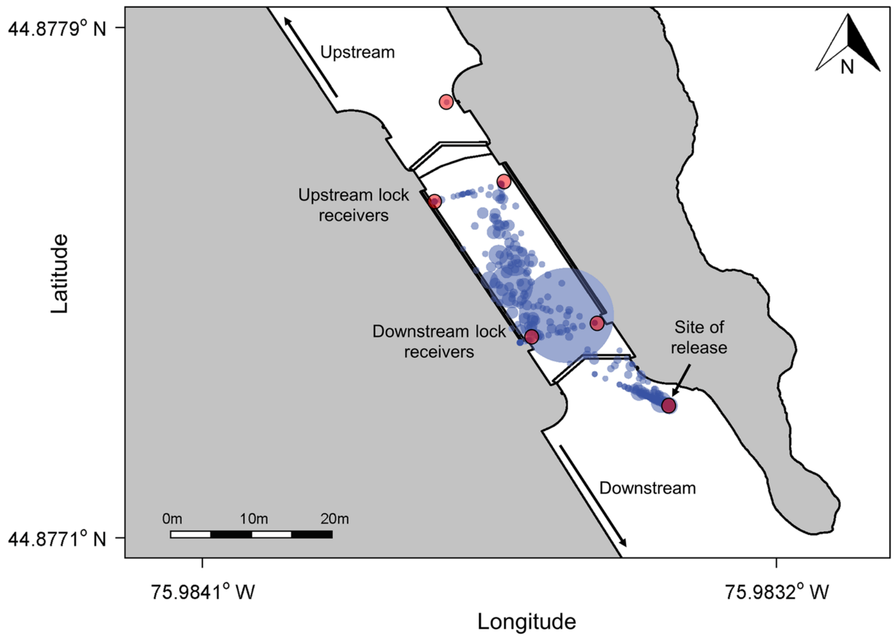

Fig. 6 Detection events for tagged round goby that entered Edmonds Lock (*N* = 9) for the full monitoring period. Red circles represent acoustic receivers: four receivers were placed directly within the lock chamber in each corner, and two receivers were placed outside the lock on the upstream and downstream side. After inspecting individual fish detections, it became clear the five receivers at the same depth (elevation) (i.e., the four lock chamber receivers and the site-of-release receiver) had overlapping detection ranges, and because our range and detection efficiency testing inside the lock chamber failed, these receivers were grouped into a single station to determine mean locations for each detection event (represented by small blue circles). Based on this figure, it appears that round goby outside the lock at the site of release may be 'heard' by downstream-lock receivers. Vice versa, fish inside the lock on the downstream side may be detected by the site-of-release receiver. Accordingly, unless detections occurred on upstream lock (chamber) receivers, the fish was not considered to have truly entered the lock. The receiver outside, upstream the lock is at a higher elevation (+ 3 m), and its detection range did not appear to overlap with the other receivers. Only one round goby was detected on the upstream receiver outside Edmonds Lock, and for only 15 min before re-entering and remaining in the lock chamber

receiver immediately outside Edmonds Lock on the upstream side for a 15 min period (Figs. 6 and 7). While this fish did indeed *pass* upstream through the lock, as it was detected exclusively outside the lock for 15 min, we do not consider it to have *dispersed* as it returned to the lock chamber and was only detected inside or downstream of the lock thereafter. It is possible that given sufficient time and low velocities, the fish could have truly dispersed. Detailed information on entry and exit pathways for each round goby detected in the lock chamber can be found in Online Resource 4.

Discussion

Although research has evaluated dispersal rates and movement patterns of round goby in both North America (Lynch and Mensinger 2012; Šlapanský et al. 2020) and Europe (Azour et al. 2015; Brandner et al. 2018; Christoffersen et al. 2019), no studies have yet used telemetry to track a new round goby invasion to inform control actions. The coverage of our telemetry array allowed for a finer-scale resolution of when fish moved either away from the release site (downstream), into the lock chamber, or above (upstream) the lock. Of the 43 round goby acoustically tagged and detected, nine (21%) were detected inside the lock. Most fish entered the lock during non-operational hours via open downstream gate valves (67%), and similarly the five fish that entered and exited the chamber also did so also through open valves, indicating that the downstream gates are indeed permeable to round goby. The elevated platform in the upstream portion of the lock (referred to as a "gate sill," see http://www.rideau-info.com/canal/img_

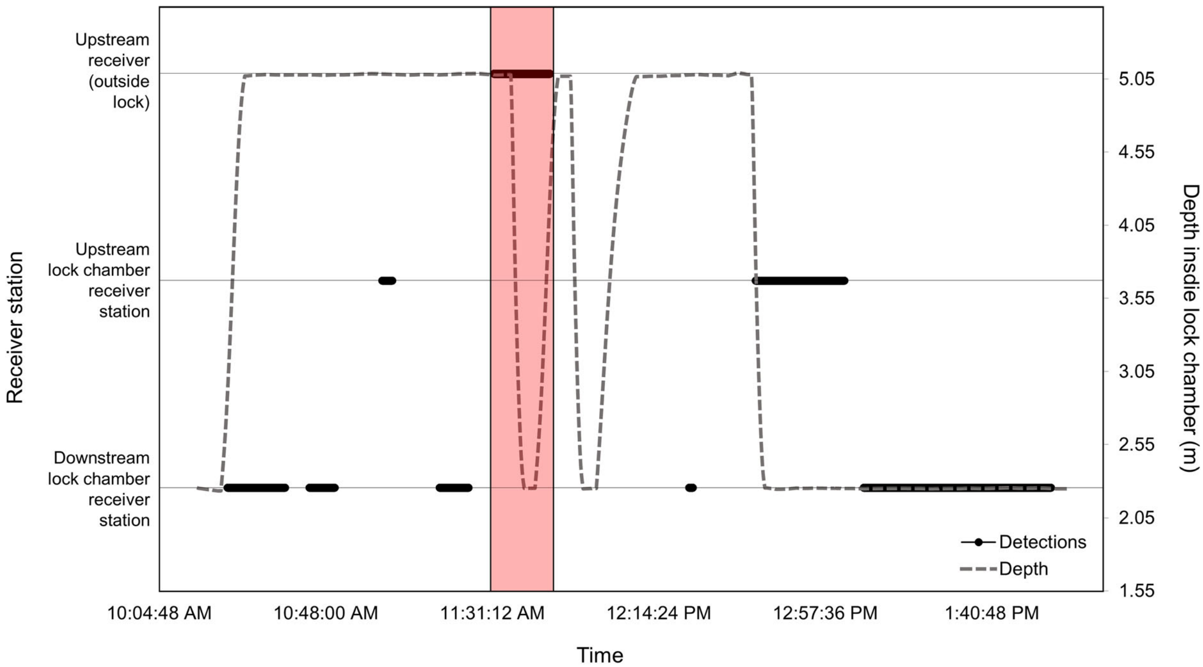

Fig. 7 Overlay of fish detections and lock operations. Fish FCA9, an 82 mm (TL) female with a large-size tag and no glue applied to the incision, is the only round goby that appears to have successfully passed through Edmonds Lock. The black, thick lines indicate fish detections, and the grey dashed line indicates the depth inside the lock chamber. The shaded red area represents the portion of the detection period when the fish was detected outside and upstream of the lock. Water levels inside the lock chamber remained consistent with upstream-water levels for 68 min indicating the upstream gate(s) were open. During this period, the round goby had the opportunity to navigate upstream and leave the lock. The fish was detected for 15 min outside of the lock, and then re-entered the chamber, concurrent with a downstream lockage. It is possible that the fish re-entered the lock when the upstream gates opened for a boat, or the fish may have been pulled back into the chamber via sluice tunnels when lockmasters were filling the lock. The fish was not detected upstream, outside of the lock again

lock_anatomy.html) and its upstream gates, however, appeared to act as an almost complete barrier to upstream movement under the conditions studied here. Except for one fish that was briefly detected for 15 min on the station immediately outside upstream of the lock, no round goby were detected upstream.

The one round goby that successfully passed upstream appeared to be able to do so as a result of normal (daytime) lock operations. By combining our telemetry data with water-level data, we were able to match lock operations with fish entry and exit times (Online Resource 4). When water levels in the lock chamber are low (i.e., same elevation as downstream water levels), the gate sill on the upstream end of the lock is exposed, physically preventing upstream passage attempts (Fig. 3A and 3C). When lock chamber water levels are high, however, round goby are presented with the opportunity to navigate the gate sill and move upstream. Although the upstream gates perpetually leak, providing some level of flow, these low velocities likely do not prevent a fish from moving upstream, and may even attract fish movement (Tierney et al. 2011). The water-level loggers detected stable, raised water levels inside the lock chamber for 68 min, indicating that the upstream gates were continuously open. It took considerable time (~ one hour) for the round goby to navigate to the elevated upstream portion of the lock chamber and exit through open upstream gates after they were opened (Fig. 7). Round goby can use a "burst-and-hold" swimming mode, whereby they hold onto substrate, with more textured surfaces aiding in a fish's ability to hold position (Tierney et al. 2011; Egger et al. 2020). It was during the extended open-gate, low-velocity timeframe that the fish was likely able to employ this swimming mode to scale the lock chamber walls, which are rough and textured (J.N. Bergman, personal observations), and traverse upstream successfully.

Recent research has indeed shown that while it may require more energy, round goby are entirely able to navigate vertical anthropogenic structures (Bussmann and Burkhardt-Holm 2020). It may be possible for round goby to avoid navigating the vertical gate sill and instead traverse a sluice tunnel to move upstream, provided the lock is full, not operating, and the tunnel valves have been left open (though according to the Edmonds Lockstation Operators, this seldom occurs; personal communication). We did not place acoustic receivers inside the tunnels because of high turbulences, so it is unclear which pathway the fish took to pass upstream. Additionally, while we can confirm that the upstream gates were open, we do not know if the intake valves were left open during that timeframe. Edmonds Lock, as well as most other locks in the Rideau Canal, is still hand-operated and requires a considerable amount of time and energy to operate; as such, lockmasters will leave gates open post-lockage if another boat is expected to arrive from that direction. In this case, leaving the upstream gates open (or potentially a tunnel valve open) resulted in an opportunity for upstream passage. The round goby that exited upstream, however, did not truly disperse, as it returned to the lock chamber. Re-entry into the lock from the upstream end could have occurred one of two ways: (1) the fish may have been pulled into a sluice tunnel and back into the chamber during lock filling or (2) it may have naturally swam back into the lock when the upstream gates were open for a lockage (Online Resource 4).

Most of the round goby in our study exhibited little or no movement, remaining near the release site for the entire study period (94 days), with only 26% (11/43) demonstrating larger-scale movements (i.e., roamers). The smaller individuals of unknown sex were all residents. Most roamers were detected in the Rideau River channel, with four individuals moving upstream against current (Fig. 5) to the site of capture. It is unclear if these four roamers exhibited true homing capabilities as we are unaware of any studies conducted to validate homing in translocated goby. However, seasonal migrations and general homing have indeed been documented in round goby (Sapota and Skóra 2005; Walsh et al. 2007; Marentette et al. 2011; Christofferson et al. 2019), and Tierney et al. (2011) noted round goby exhibit a general pattern of positive rheotaxis (i.e., fish turn to face oncoming current) and move upstream more than downstream. Because of this tendency to move upstream, it may be that these fish movements, against current to return home, were directed and not random. Additionally, Marentette et al. (2011) documented male round goby to move more than females; while we lacked the sample size to resolve sex-specific movements between residents versus roamers, four of the five individuals that were detected at stations farthest from the site of release were male.

Given their benthic lifestyle, lack of swim bladder, and small home ranges, site fidelity and/or a preference for inactivity appears common for round goby (Wolfe and Marsden 1998; Ray and Corkum 2001; Šlapanský et al. 2020). Similar to our findings, other research has indicated at least a portion of a round goby population will undertake larger-scale range expansions, pioneering new areas (Gutowsky and Fox 2011; Brownscombe and Fox 2012; Šlapanský et al. 2020). However, the rate at which individuals disperse can vary both spatially and temporally. During winter months, when temperatures are very low in Ontario, it is likely that round goby are relatively inactive (Lee and Johnson 2005). In spring (a season our study did not capture) and autumn (a season when most of our tags were no longer being detected), however, round goby range expansions likely occur (Brownscombe and Fox, 2012); thus, we may have missed larger-scale movements during these times. For example, using capture-mark-recapture methods, Lynch and Mensinger (2012) found 89% of individuals in the Duluth–Superior harbour of Lake Superior were stationary, with occasional movements of up to 50 m/day, though few large-scale movements occurred during warm-temperature months (e.g., June and July). The most rapid rate moved by round goby was documented by Christofferson et al. (2019) via acoustic telemetry in the Baltic Sea, where fish covered distances 1.5–2 km in less than one day as part of overwintering migrations. In our study, the farthest a fish dispersed was 500 m after 27 days, which generated a maximum dispersal rate of 18.5 m/day, a rate similar to Šlapanský et al. (2020) (22.33-m/day downstream). The relatively short battery life (i.e., maximum 131 days) of acoustic tags suitable for round goby in the Rideau Canal limited our ability to track individuals long-term; as such, it would be useful to conduct subsequent telemetry studies in late fall and early spring, immediately before and after ice-on and ice-off, respectively, to evaluate potential seasonal differences in movements.

We did not find size-biased movements, though there has been debate about whether smaller or larger round goby are the pioneers that lead an invasion front into new areas. Where Šlapanský et al. (2020), Brownscombe and Fox (2012), and Bergstrom et al. (2008) found that the smallest round goby were pioneers (possibly as a result of being outcompeted by larger individuals), Gutowsky and Fox (2011), Brandner et al. (2013), and Brandner et al. (2018) documented round goby at the invasion front to be significantly larger. Reports of sex ratios at invasion fronts are also mixed (e.g., female-biased: Brandner et al. 2013, Brandner et al. 2018, Janáč et al. 2019; male-biased: Corkum et al. 2004; Azour et al. 2015), even within the same river system. For example, in the Trent-Severn Waterway—an analogous system to the Rideau Canal also located also in Ontario—Gutowsky and Fox (2011) found invasion fronts to be male biased, whereas Brownscombe and Fox (2012) found individuals in newly expanded areas to be female biased. There additionally have been instances where no sex-bias was recorded at the invasion front (i.e., 1:1 sex ratio; Šlapanský et al. 2017). It is unclear what may be causing the disparity in sex ratios across different studies, but it is possibly a result of differing sampling time/season, sample techniques, and/or could simply be the result of high variation within and among populations (Šlapanský et al. 2017). Observed sex ratios could also be a product of invasion pathway; for example, downstream dispersal of larval round goby (which have been collected over 2 km from known spawning habitat; Hensler and Jude 2007) would likely result in a downstream population with no sex bias and smaller individuals compared to the (source) upstream population. Establishing how a new population was introduced (e.g., larval drift versus bait bucket), and the size- and sex-specific movements of that population, could be vital in determining the age of the invasion and using that information to decide what management actions might be most effective in controlling that specific population.

It is our belief the round goby population we sampled in the Rideau Canal represents a newly-established source population and invasion front. First, the Rideau Canal is a highly managed system that is regulated and monitored closely by Parks Canada, which often entails draining locks and/or surrounding areas to conduct maintenance during the non-navigation season. Fish salvages are conducted when areas are drained for larger infrastructure projects, with species identification and abundance recorded; indeed, this is how round goby were first discovered in the Rideau Canal. The only other lockstation where round goby have been reported in the Rideau Canal is at the triple-flight Kingston Mills Lockstation (see http://www.rideau-info.com/canal/locks/46-49-kingstonmills.html), the southern terminus that connects the system to Lake Ontario (where an established, known population of round goby exists; Fig. 1). Round goby have only been reported in the most downstream lock chamber (lock 49, closest to Lake Ontario), with the exception of two individuals being reported in the basin between lock 46 and 47, but not upstream of the lockstation in Colonel By Lake (EDDMapS 2021). This again suggests that locks, for the most part, serve as natural barriers to round goby upstream passage. Second, we were unable to capture round goby using methods commonly employed in areas with high densities. For example, in Hamilton Harbour, Lake Ontario, where round goby can be found in high abundances, minnow traps are very effective (Mehdi et al. 2021). In contrast, minnow traps deployed in our study area were ineffective, regardless of the time of day or the length of time deployed, or the bait used. Our failure to catch round goby in minnow traps suggests a low-density population, another characteristic of a newly established invasion. Although we cannot precisely state the age of the invasion, based on round goby being exclusively found in a central portion of the waterway, at low densities, and with a female-biased sex ratio, we believe this round goby population in the Rideau Canal is < 5 years old (introduced earliest in 2014; see Bergstrom et al. 2008; Thorlacius et al. 2015; Brandner et al. 2018).

Limitations

Anthropogenic waterways and canals are well recognized globally as vectors of exotic species transfer (Daniels 2001; Panov et al. 2009; Marsden and Ladago 2017; Lin et al. 2020). Though navigation locks have been reported to lack the necessary attractant flows to facilitate upstream dispersal (Coker 1929; Moen et al. 1992; Wilcox et al. 2004), research has nevertheless shown that fish can use locks to move upstream (Tripp et al. 2014; Kim and Mandrak, 2016; Lubejko et al. 2017; Finger et al. 2020). Round goby have used canals in North America to disperse (e.g., the Chicago Ship and Sanitary Canal, Kolar and Lodge, 2000, Wilcox et al. 2004; New York State canal system, George et al. 2021; Welland Canal et al. 2016); however, fine-scale movement patterns and dispersal methods of round goby in canals and via locks are not well studied or understood. In this context, our study provides one of the first telemetry-based accounts of round goby movement, though there are several limitations that should be acknowledged. First, 53% of tagged fish were detected for seven or fewer days (Online Resource 1, Fig. S5). This short detection time is likely linked with the porosity of the acoustic array in the downstream riverine areas where detection range is < 25 m and receivers were widely spaced. It is also possible that the detection range and efficiency of receivers inside and near the lock varied during lockages, as these events produce considerable anthropogenic noise. Tag transmissions (from range and detection testing) were not detected frequently or consistently enough to analyze lockage-specific receiver range and efficiency. However, we did find that tag transmissions were sporadically detected during both operating and non-operating hours, suggesting that other aspects of the environment beyond turbulence and flows from lockages are responsible for poor detection efficiencies (e.g., surrounding hard surfaces that can refract acoustic signals). Because round goby are benthic and prefer rocky habitats, tagged fish may have been using benthic refuge in ways that prevented tag transmissions from being heard by receivers. Some of our fish may have been eaten by predators, which then swam outside the detection range of the array. However, given that this is a new invasion site, we predict reduced predation because of low round goby densities and because local predators may still be naïve to round goby as a prey item (Brownscombe and Fox, 2013). We did not precede this field study by conducting a laboratory experiment to assess tagging effects as we wanted to focus on rapidly deploying tags in fish in the field to quickly provide information to managers and also to assess fish movements as early in the invasion as possible. Behrens et al. (2017) found that round goby survive the tagging process with tags that constitute up to 4.3% of their body mass, though 6.7% of their tagged fish showed signs of tag expulsion when the tag burden was $> 3\%$. As such, we acknowledge the possibility that the 15 individuals who were detected only at the site-of-release receiver may have simply been expelled tags (Online Resource 1, Table S5). Nevertheless, round goby are known to have small home ranges, and the site of release constituted ideal round goby habitat with an abundance of food (zebra mussels *Dreissena polymorpha*; Raby et al. 2010) and rocky refuge. Likely an artifact of battery life, the larger tags were detected for considerably longer amounts of time compared to smaller tags (average of 15.63 more days; 0.04-g heavier). For others conducting work on small-bodied fish, the larger tags may be worth using exclusively. Finally, although no statistical effects of glue application to the surgical site were detected, 73% of roamers did not have glue applied to their incision, and so it may be that glue was limiting fish movement.

Management implications and future directions

Managing invasive fish passage through locks on the Rideau Canal poses a unique challenge, as any strategies implemented cannot negatively impact navigation or boater safety, and ideally would not (further) restrict native aquatic wildlife movements (e.g., fish, turtles). Electrical barriers, for example, would be inappropriate to use in this system, which is highly used by recreational boaters and paddlers (kayaks, canoes, paddle boards), and which would prevent native species movements and migrations. Free-standing structural barriers, like gates or screens, would also be difficult to implement as they would have to pose no impact to navigation (i.e., not be placed in the channel) and not affect other native species (especially migratory at-risk species, like American eel *Anguilla rostrata* and snapping turtle *Chelydra serpentina*, which Parks Canada is federally mandated to protect). Carbon dioxide barriers could be used to reduce round goby passage and may be applicable to the Rideau Canal as they do not interfere with navigation or river flow (Cupp et al. 2021). However, testing to date indicates that most species and fish sizes show avoidance behaviours to carbon dioxide barriers (Treanor et al. 2017; Rahel and McLaughlin 2018), and so again this option would fully fragment the system, not allowing for selective passage strategies (i.e., permitting and restricting passage to native and invasive species, respectively). Acoustic (Isabella-Valenzi and Higgs 2016) and/or pheromone traps (Corkum et al. 2008; Bajer et al. 2019) could be deployed in higher density regions to passively capture round goby and control the local population, though these methods require a high level of sustained effort and would not result in eradication.

Eradication of aquatic organisms, even when restricted to small water bodies, has proven difficult (Rytwinski et al. 2019). When management efforts to eradicate or control aquatic species have indeed been successful, it was because action was taken quickly (Simberloff 2014) and/or sufficient funds and personnel were available to achieve management goals (Larson et al. 2011). Although eradication attempts of round goby have been unsuccessful and costly (e.g., Dimond et al. 2010), the population in the Rideau Canal is likely a new invasion and so there may be an opportunity for control by preventing further spread through a combination of several conservation measures. To reduce the likelihood of upstream dispersal, two actions—modifying infrastructure and lock operations—could be effective. Two-thirds of tagged round goby that entered the lock did so during non-operational hours through open downstream valves. Because valves on the downstream gates must be left open during non-operational hours, a grate or screen could be attached to the valves to prevent round goby from entering. These screens, however, would have to be maintained for biofouling and debris removal, and it could increase drag therefore slowing operation (i.e., draining) time. Alternatively, a relatively minor infrastructure modification could be implemented, whereby a water-release valve above the highest known downstream water level is installed on the downstream gate. Research suggests that in-stream barriers which force round goby to overcome gravity (i.e., climb an air-exposed, vertical wall) should be impassable (Pennuto and Rupprecht 2016); as long as the overflow valve does not slowly drain water along the gate, round goby should be incapable of exploiting it as an entry pathway. As the Rideau Canal is a National Historic Site of Canada, historical elements must be preserved, so there may be some restrictions to gate modifications. However, given that gates are wooden it may be a low-cost solution that would not need to be maintained (Valerie Minelga, Parks Canada, personal communication). Second, keeping gate doors and tunnel valves closed unless necessary—a change in lock operations—would reduce the dispersal opportunities. Recommendations to close upper and lower gates when not in use to prevent fish from passing through locks has been suggested for other navigation systems as well (e.g., Soo Locks, Sault Ste. Marie, Michigan; LSBP 2014). To better integrate movement and velocity data, future work could investigate the energetic demands of movement paths and associated swimming velocities encountered, in lab and field scenarios, to inform lock-specific management. This was outside the scope of this article given the coarseness of our detection data (i.e., 20 s signal transmission rate and/or sporadic detections, see Fig. 7 and Online Resource 3). Modifying lock-and-dam infrastructure and operations to minimize invasive species passage has been investigated (Lubejko et al. 2017; Fritts et al. 2021; Zielinski and Sorensen 2021), though we are not aware of any such work with round goby.

The solution to managing round goby downstream dispersal is less clear. In 2020 and 2021, the two years following our telemetry tracking study, free diving and snorkel surveys were conducted in the region downstream of Edmonds Lockstation and a higher abundance of round goby were observed near the station 500 m from the original site of capture, indicating downstream dispersal is occurring as expected. We did not track movements of juveniles (< 50 mm), and given that juvenile round goby have been documented to disperse downstream rapidly (Tavares et al. 2020), we may have missed key insights into range expansion. However, the number of round goby observed markedly decreased close to Kilmarnock Lake (Online Resource 1, Fig. S1), ~ 1.5 km downstream of Edmonds Lockstation. Kilmarnock Lake is a shallow, heavily vegetated lake with mostly mud and sand bottom; poor habitat characteristics for round goby (Young et al. 2010). As such, the lake may slow downstream dispersal. In early spring when macrophytes are not yet dense, round goby may traverse this area more easily, though if there is no suitable habitat then further dispersion would be minimized. Rocky substrate is essential for round goby to carry out their life cycle (Kornis et al. 2012), and so the wetland-like Kilmarnock Lake may at the very least impede colonization opportunities, though we note that high numbers of round goby have indeed been captured on muddy, vegetated shoals in the nearby St. Lawrence River, Québec, Canada (Morissette et al. 2018). Similar lock operation modifications, whereby gates are kept closed when not in use, could be implemented at the next downstream lock to minimize dispersal into the northern portion of the waterway.

Finally, and of arguably greatest importance, are public education and outreach efforts. Despite the illegality of transporting and releasing bait fish in Ontario, it is highly likely that round goby were introduced into the Rideau Canal via a bait bucket release event. Although a population of round goby exists in Lake Ontario, it is unlikely that they naturally dispersed upstream through 14 lockstations undetected, and anglers have indeed been implicated as highly mobile invasion vectors (Keller and Lodge 2007; Bronnenhuber et al. 2011; Kilian et al. 2012; Drake and Mandrak 2014). Management and conservation efforts that promote public awareness, stewardship for the natural environment, and compliance to regulations should be pursued to reduce any additional unwanted introductions into new areas.

Conclusion

This study used biotelemetry as a tool to investigate fish behaviour at a new round goby invasion in the Rideau Canal, providing data to help inform conservation actions at this location. We recommend future studies examine passage rates and movements of both native and invasive fish in the Rideau Canal, as efforts to minimize round goby dispersal may also reduce upstream movements of native fishes (i.e., resulting in a need to develop selective passage strategies; Rahel and McLaughlin 2018; Altenritter et al. 2019). Implementing and evaluating management strategies, like modifying lock operations and infrastructure, may provide options to control this invasion. Although previous work has been conducted to evaluate effects of acoustic tagging on round goby (Behrens et al. 2017), no work has been done using individuals as small as the fish in our study. Additionally, predation-type acoustic tags have shown promise (Halfyard et al. 2017), and so it would be useful in the future to use this technology to determine if and/or how many tagged goby are preyed upon. Any conservation strategies implemented must be monitored to verify effectiveness. As with most invasive species management efforts, outreach campaigns will be vital to spread conservation messaging and minimize future round goby introductions. With more than 60,000 km of canals with anthropogenic barriers worldwide (Revenga et al. 2000), many of them highly-managed waterways analogous to the Rideau Canal, our work may serve as a model for future use of telemetry to rapidly assess invasive species movement in other systems in North America and beyond.

Acknowledgements We sincerely thank the 2019 Parks Canada Lock Operators of Edmonds Lockstation, Dominic Peladeau and John Gauthier, for providing support in acoustic receiver deployment inside the lock chamber and for sharing critical information about daily lock operations. We thank Dr. Dirk Algera and Benjamin Hlina for support in statistical analysis. Thank you to Valeria Minelga and Dr. Chantal Vis for providing useful suggestions and comments on an early version of this manuscript that greatly improved it. Two undergraduate research assistants, Brenna Gagliardi and André Killeen, provided key field support and so we thank them for their efforts. We thank the heritage researcher and author Ken Watson for providing permissions to use his maps of the Rideau Canal as a template for Fig. 1. Finally, we sincerely appreciate the thoughtful input of two referees.

Funding Funding for this work was supported by an NSERC Strategic Project Grant focused on the Rideau Canal Waterway. J.N.B. and K.L.N are each funded through Natural Sciences and Engineering Research Council of Canada (NSERC) Postgraduate Scholarships. JRB is funded by the NSERC Discovery Program. Acoustic telemetry equipment was provided by the Realtime Aquatic Ecosystem Observation Network (RAEON), funded by the Canadian Foundation for Innovation (CFI) and Ontario Ministry of Research, Innovation, and Science.

Availability of data and material The datasets generated and/or analysed during the current study are available from the corresponding author on reasonable request.

Code availability The code used in the current study are available from the corresponding author on reasonable request.

Declarations

Conflict of interest The authors declare that they have no conflict of interest.

Ethics approval Experimental protocols were approved by the Carleton University Animal Care Committee (AUP no. 110723) in compliance with the guidelines of the Canadian Council for Animal Care.

Consent to participate All authors consented to participation in the manuscript.

Consent for publication All authors consent to the publication being submitted for peer review.

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