Hydrobiologia (2015) 742:327–338
DOI 10.1007/s10750-014-1996-0

PRIMARY RESEARCH PAPER

Seasonal movements and residency of small-bodied fish in a north temperate urban watershed demonstrate connectivity between a stream and stormwater drain

S. M. Bliss · J. D. Midwood · K. M. Stamplecoskie · S. J. Cooke

Received: 10 March 2014 / Revised: 2 July 2014 / Accepted: 21 July 2014 / Published online: 12 August 2014

Abstract Despite their often physical connection, neighbouring stormwater drains and urban streams are typically managed quite differently; with drains mostly regarded as poor fish habitat. The goal of this study was to evaluate the interconnectedness of an urban stream (Watts Creek) and adjoining earthen surface stormwater drain (Kizell Drain) from the perspective of fish residency and movements over an entire year. Using a stationary passive integrated transponder (PIT) array, we quantified and compared the direction of movements among Watts Creek, Kizell Drain, and the area downstream of their confluence (herein termed Main) for four common stream fishes. We also determined the residency time (percentage of total time in days) within each of these reaches by combining data from the array and recaptured (with electrofishing and identified with hand-held PIT reader) or portably detected (with mobile PIT reader) fish. While the movements of creek chub (*Semotilus atromaculatus*) and central mudminnow (*Umbra limi*) varied across seasons, creek chub resided significantly longer in Watts, while central mudminnow spent more time in Kizell and Main. Longnose dace (*Rhinichthys cataractae*) moved into and resided most often within Watts. The movements and residency time for white sucker (*Catostomus commersonii*) did not vary among the reaches. We conclude there is a high degree of connectivity between Watts Creek and Kizell Drain and that, with the exception of longnose dace, the three other species utilize the habitat available in Kizell. This study demonstrates the biological potential of earthen stormwater drains and as a result we recommend these systems be managed as a functional component of urban watersheds.

Keywords Stream fish · Urban ecology · Winter · PIT · Stormwater drains

Handling editor: Alison King

S. M. Bliss (✉) · J. D. Midwood ·
K. M. Stamplecoskie · S. J. Cooke
Fish Ecology and Conservation Physiology Laboratory, Department of Biology, Carleton University, 1125 Colonel By Drive, Ottawa, ON K1S 5B6, Canada
e-mail: bliss.shireen@gmail.com

Introduction

Streams and rivers are the hydrological 'highways' that connect various landscape elements (including riparian areas) and serve as corridors in urban environments (Walsh et al., 2005). Indeed, stream corridors provide opportunities for fish and wildlife to move about otherwise fragmented habitats (Puth & Wilson, 2001). However, intensification and expansion of urban centres mean it is important to understand the influence of land use change on individuals, populations and ecosystems. Impervious surface cover and stormwater management systems designed to efficiently drain water runoff out of cities are commonly part of the land use changes in urban landscapes (Paul & Meyer, 2001). Studies of the impacts of stormwater management on streams have primarily examined stream morphological changes, transportation of contamination and sediment, and changes in macroinvertebrate or fish community structure (Berkman & Rabeni, 1987; Sponseller et al., 2001; Hatt et al., 2004). Less is known about fish dispersal and movement within streams and associated stormwater drainage systems in urban areas.

The study of fish movement describes the mechanism fish use to meet biological requirements (e.g. foraging and breeding) and respond to changes in environmental or biotic conditions (e.g. water quality, predator avoidance) (Rodriguez, 2002). Understanding fish movement in streams enables researchers to determine the habitat needs of various species, define spatial boundaries of populations, identify migration patterns and corridors, and characterize the effects of physical barriers and environmental disturbance (Freeman, 1995; Lucas & Baras, 2000; Belanger & Rodriguez, 2002). Movement of stream fishes has been studied extensively, initially with simple mark-recapture approaches (e.g. Funk, 1957), but later and more thoroughly with telemetry (e.g. salmonids, Aarestrup et al., 2003; endangered species, Knaepkens et al., 2004; invasive species, Cookingham & Ruetz III, 2008). Innovations in passive integrated transponder (PIT) technology provide new opportunities for the study of entire stream fish communities given that tags are inexpensive, small, and can last for years (Gibbons & Andrews, 2004; McEwan & Joy, 2011). PIT-tagged fish can be located manually with mobile tracking systems (Zydlewski et al., 2001; Cucherousset et al., 2010), monitored as part of traditional mark-recapture studies (Dieterman & Hoxmeier, 2011) or tracked using automated stationary PIT detection arrays (Teixeira & Cortes, 2007). PIT systems can also be used in winter including under ice (or through ice), which is particularly useful for monitoring fish movements in north temperate regions (Roussel et al., 2004).

The impacts of human development on stream fish have been well documented (Klein, 1979; Schlosser, 1991; Roy et al., 2008), but most of this work has been focused on changes in stream fish assemblages (e.g. Wichert & Rapport, 1998) rather than movements. Research on movement has typically focused on migration barriers (culverts) and changes in flow and temperature (Scott et al., 1986; Marchetti & Moyle, 2001; Norman et al., 2009) such that we are unaware of any studies that have explored the connectivity between earthen surface drains and streams. Earthen surface drains (also known as ditches or swales) are only one of many types of stormwater drains (concrete vs earthen and subsurface vs surface; Djokic & Maidment, 1991) that are open to the surrounding environment, flow above ground, and may be physically connected to streams. Despite physical connectivity, in most jurisdictions, drains and streams are treated quite differently. Drains are subject to cleaning (i.e. use of heavy equipment to maintain an open channel) at regular intervals or when deemed necessary and are typically not regarded as fish habitat in a regulatory context. In general, most drains are comparatively simple channels, often with less horizontal and vertical sinuosity relative to natural streams. However, it is important to recognize that historically many surface drains were natural stream environments prior to their channelization and management for stormwater conveyance (Kaushal & Belt, 2012). Knowledge of the extent to which fish use earthen surface drains and the level of connectivity between streams and drains on a seasonal basis would be useful in identifying the ecological value of these systems. Furthermore, due to practical considerations, most studies of fish movements in streams are conducted during the summer resulting in major gaps in our understanding of how fish in north temperate urban streams behave or are distributed throughout the entire year including the winter months (Cunjak, 1996; Brown et al., 2011).

Using the Watts Creek watershed in Kanata, Ontario, Canada, we evaluated the movements and residency time of four common stream fishes, creek chub (*Semotilus atromaculatus*), central mudminnow (*Umbra limi*), longnose dace (*Rhinichthys cataractae*) and white sucker (*Catostomus commersonii*) between an urban stream (Watts Creek) and an adjoining earthen surface stormwater drain (Kizell Drain). Watts Creek and Kizell Drain are distinct in their substrate composition, in-stream habitat, legislative management and origin. Relative to Watts Creek, the aquatic habitat in Kizell Drain is more disturbed as a result of channelization. This field study focused on the confluence between Watts Creek and Kizell Drain, which had three reaches that branched out: Watts and Kizell (upstream of the confluence), and Main (downstream of the confluence). Our first objective was to compare the extent of fish movement among these reaches using a stationary PIT detection array over a 1-year period (including under the ice). We predicted that the degradation of the habitat in Kizell would result in proportionally less movement into the drain. Given the availability of 24-h movement data from the stationary PIT array, we also explored diel detection patterns to provide a more detailed understanding of the fishes behaviour. Our second objective was to compare the residency time (percentage of time in days) among the reaches using data from the fixed detection array supplemented with additional fish positions obtained via mark-recapture of PIT-tagged fish and infrequent manual tracking outside of the area where the array was installed. Our findings are discussed in the context of urban stream ecology and the interconnectedness of streams and storm surface drains.

Materials and methods

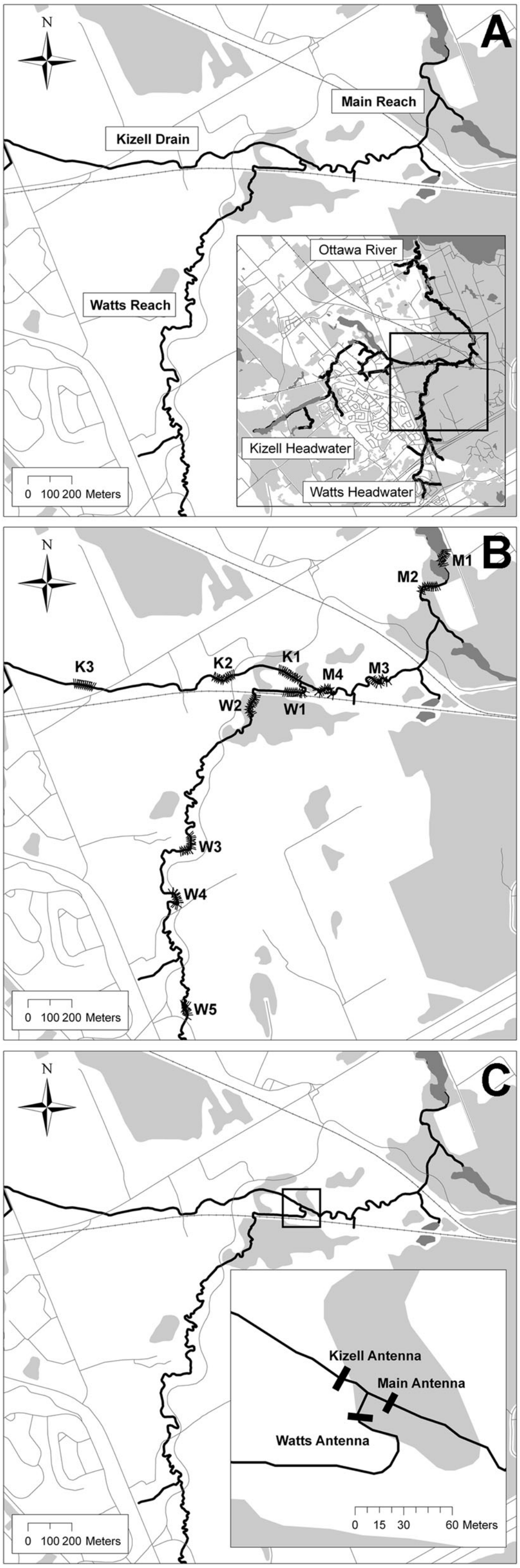
Study area

Watts Creek (45°20′42″N, 75°52′19″W) is a tributary of the Ottawa River and located in Kanata, Ontario, Canada, the largest suburb in the Ottawa region. Precambrian and Palaeozoic bedrock overlain with a layer of silt and clay makes up the soil composition of the Watts Creek watershed (~2500 ha). Approximately 47% of the land used is for agriculture, 35% is developed, and 18% is undeveloped. The creek originates in the Katimavik-Hazeldean community of Kanata and flows through a residential area. Watts Creek is groundwater fed with stormwater inlets from surrounding areas including Kizell Drain, an earthen municipal surface drain originating at the Beaver Pond stormwater management pond (near Walden Dr., Kanata, ON). The confluence between Watts Creek and Kizell Drain is the focal point of this study in which there are three reaches branching out (Fig. 1A). These reaches are herein referred to as Watts (~2.9 km of the creek upstream from the confluence), Kizell (~1.5 km of Kizell Drain upstream from the confluence) and Main (~1.7 km of the creek downstream from the confluence). Low sinuosity (1.1) of Kizell is the result of past channelization; however, the section included in this study has not been cleaned with heavy equipment for >10 years. Regardless, the in-stream habitat of Kizell is the narrowest (channel width: 4.57 m) and shallowest (channel depth: 0.55 m), dominated by runs and fine sediments (98 and 86%, respectively; pools and riffles: 1% of each; medium and course sediment: 11 and 4%, respectively) with little in-stream structure (typically less than 20%). In contrast, Main and Watts are more sinuous (1.8 for both) with higher habitat complexity, a mix of runs (66 and 72%, respectively), pools (10% for both) and riffles (25 and 19%, respectively), as well as a higher prevalence of medium (24 and 29%, respectively) and coarse (16 and 15%, respectively) sediment and in-stream structure (45 and 27%, respectively) than found in Kizell (see Maarschalk-Bliss, 2014 for additional detail). We considered Kizell a more degraded system relative to Main and Watts because of the lower sinuosity, habitat complexity, sediment diversity and in-stream cover (Goldstein & Meador, 2005; Walsh et al., 2005).

Fish sampling and tag implantation

Fish were sampled using single-pass backpack electrofishing (Model 12, Smith-Root, Vancouver, WA, USA) from 26 March 2012 to 8 November 2012, and again from 22 April 2013 to 30 May 2013 throughout Watts Creek and Kizell Drain. Sampling frequency and location varied throughout the study. Most of the sampling and tagging occurred within twelve 100 m transects approximately once per month throughout the study period (for a total of 9 occasions; Fig. 1B). Additional sampling between transects occurred within the first 5 months to increase the total number of tagged fish in the system. This included 8 occasions where specific sections were targeted and 1 occasion where we sampled the whole system to include areas that were infrequently sampled (each step increase in the number of tagged fish in Fig. 2 represents an occasion of active sampling).

Since detection efficiency of tags increases with size (Burnett et al., 2013), the largest appropriate tag size for each fish was used to ensure the highest possible detection efficiency for every individual. Consequently, two different sized tags were used, 12 mm (12 × 2.15 mm) and 23 mm (23 × 3.65 mm). In general, fish of approximately 70–130 mm in total length (TL) were tagged with 12 mm tags, and larger fish (>130 mm (TL)) were tagged with 23 mm tags. Central mudminnow and longnose dace



◀**Fig. 1** Map of the Watts Creek study site showing the **A** location of site within the watershed (inset) and location of the reaches, **B** transects where regular sampling occurred, and **C** the PIT array set-up around the confluence of the stream and stormwater drain. The direction of water flow is from the west to east for Kizell and from the south to north for Watts and Main. The sampling sites in each reach are numbered sequentially in an upstream direction. The confluence is located downstream of sites K1 and W1, and upstream from site M4. The *thin grey lines* are roads and pathways, while the *thin hatched-lines* are train tracks. The *lighter grey shaded area* represents heavily vegetated areas with the *dark grey* representing water bodies

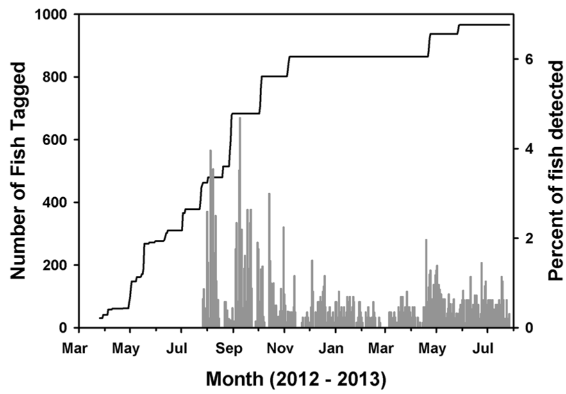


Fig. 2 The number of fish tagged (*black line*, *left axis*) and the percentage of tagged fish detected (*dark grey bars*, *right axis*) each day over the course of the study. Tagging initiated on 26 March 2012, the PIT array was active on 27 July 2012, and the study ended on 27 July 2013. Each *step* increase in the number of fish tagged represents an event when active sampling and tagging occurred (18 in total). Sampling frequency was higher in the beginning of the study in order to increase sample sizes

were only tagged with 12 mm tags, while creek chub and white sucker received either sized tag depending on the length of the individual. The total length of the fish tagged ranged from 71 to 216, 70 to 126, 72 to 120 and 71 to 255 mm for creek chub, central mudminnow, longnose dace and white sucker, respectively (Table 1). Only adult creek chub (>76 mm), central mudminnow (>64 mm) and longnose dace (>61 mm), and juvenile white suckers (<255 mm) were included in the analyses (Scott & Crossman, 1998; Coker, Portt, & Minns, 2001). Each fish was identified to species, the total length was measured, and they were tagged with a uniquely coded HDX PIT tag (Oregon RFID, Portland, OR, USA). Using a 12-gauge needle or scalpel, a small puncture (<3 mm) for 12 mm tags or an incision (<5 mm) for 23 mm tags was made to the side of the ventral midline anterior to the pelvic girdle

Table 1 The four species tagged with the mean (±standard deviation) and minimum total lengths (TL) tagged, number of fish tagged with either a 12 mm or 23 mm tag in each reach, and the number of 12 mm and 23 mm tags that were detected or recaptured over the course of the entire study

Species	TL (mm)	Minimum TL (mm) tagged	Number of fish tagged with 12 mm (23 mm)			Number of 12 mm (23 mm) tags detected
			Kizell	Main	Watts	
Creek chub *Semotilus atromaculatus*	118 ± 28	71	23 (11)	25 (19)	230 (85)	77 (44)
Central mudminnow *Umbra limi*	84 ± 9	70	39	120	46	115
Longnose dace *Rhinichthys cataractae*	90 ± 9	72	1	58	174	55
White sucker *Catostomus commersonii*	182 ± 113	71	21 (7)	79 (43)	74 (83)	63 (43)

and tags were inserted into the coelomic cavity. Air exposure and handling time were minimized (<1 min) and tagged fish were kept in a recovery bucket for a short period (<30 min) before being returned to the creek. No anaesthetic was needed given that most fish were still in a sedated state as a result of capture by electrofishing and that anaesthesia was not needed to restrain fish for this simple procedure. A GPS coordinate was used to indicate the location where fish were tagged and released.

Tracking and observations

To monitor fish movements between Watts Creek and Kizell Drain, three pass over antennas were installed in Main (1.3 × 3.25 m; length × width), Watts (0.84 × 2.1 m^2), and Kizell (1 × 2.5 m) approximately 5–7 m from the confluence centre, resulting in distances of 10–13 m apart from each other (Fig. 1C). The use of one PIT antenna at the entrance of each reach only allowed for the evaluation of whether a fish entered a reach, not how far they travelled into each reach. The width of the antennas corresponded to the width of the stream where they were located. The antennas were secured to the stream floor with large, heavy rocks that were placed between two sheets of diamond mesh polyethylene fencing material with 12 awg THHN electrical wire tied along the perimeter. The antennas were tuned manually with remote tuner boxes and connected to a MultiAntenna HDX Reader with Twinax cable (equipment obtained from Oregon RFID, Portland, OR, USA).

For each sampling occasion, we scanned all fish captured that were a minimum of 70 mm (TL) for the presence of a tag. A portable HDX Backpack PIT Reader with attached antenna pole (Oregon RFID, Portland, OR, USA) was infrequently (3 occasions between May and July 2012) used to scan the whole system within the study area for tagged fish. The operator swept the antenna from bank to bank across the surface of the water while moving downstream. In an attempt to improve detection potential in deep pools, the antenna was submerged below the surface to a maximum depth of 30 cm. Scanning efficiency within this system was low because the streambed was predominantly composed of fine sediments (clay and silt) that slowed the pace of the operator. Fish were frequently observed swimming faster than the operator, therefore, despite previous work demonstrating the efficiency of tracking in a downstream direction (Cucherousset et al., 2010), scanning was discontinued after July 2012. Most of the previous work using this method focused on salmonids, which may have a tendency to exploit structural complexity and hide, enabling PIT detection, rather than attempting to escape. While sampling and using the portable PIT reader, any fish that had already been tagged were considered a recapture. Recaptures allowed us to identify the locations of fish that did not move past the array.

Array efficiency

The detection efficiency of each antenna was calculated as the number of actual passages (number of tags successfully detected by an antenna) divided by the number of known passages (the number of tags known to have passed an antenna based on detections at another antenna or recaptures; Zydlewski et al., 2006). For example, if a fish was tagged in Main, the first detection/passage should occur on the Main antenna resulting in one actual and one known passage. However, if the fish was first detected on Kizell or Watts then it failed to be detected at Main, and would result in zero actual and one known passage. The detection efficiencies were 83, 62 and 71% for Kizell, Main and Watts, respectively. The calculated efficiency of the Main antenna was lower than the other antennas likely because during late winter (9 Apr–9 May 2013) an animal chewed through one of the wires and the antenna was non-functional until we discovered and resolved the issue. Array performance is understood to be influenced by environmental variables (i.e. variable flows and weather) and individual fish behaviours (Aymes & Rives, 2009).

Data analysis

For the first component of this study, we defined movement between two reaches as the detection of a tag from one antenna to another with a minimum of 30 s between detections. Six possible directions of movement between reaches were identified as follows: Kizell to Main, Kizell to Watts, Main to Kizell, Main to Watts, Watts to Kizell and Watts to Main. For each individual fish, the extent of movement was calculated as the proportion of movement in a given direction (e.g. 0.25 Kizell to Main, 0.5 Main to Kizell, and 0.25 Watts to Kizell). Then, for each species-season and species, we calculated the overall average percentage of movements in each of the six directions. Diel detection patterns were used as a surrogate for fish activity in the area around the antennas and were visualized by plotting the number of detections by the hour of day for the entire study period.

For the second component of this study, residency time was determined by counting the number of days an individual fish spent within each reach relative to the total number of days the fish was available for detection after being tagged. The location of a fish was determined by tracking its movement through the PIT antenna and using other locations identified with mark-recapture or a portable backpack PIT reader. These calculations were converted into percentages because the total number of days each fish was available for detection varied across the study period.

A Kruskal–Wallis analysis of variance was used to test if the proportion of movements and residency time among the reaches differed significantly, and Tukey–Kramer HSD comparisons determined specific group differences following a significant result. Statistical analyses were conducted when sample sizes were greater than 5 fish ($n > 5$). All statistical analyses were deemed significant at $P < 0.05$ and performed using JMP statistical software (version 7.0.1; SAS Institute Inc., NC, USA).

Results

A total of 1,138 fish were tagged, of which 396 fish (34.8%) were either detected or recaptured (Table 1). Creek chub, longnose dace and white sucker were primarily caught and tagged in Watts (80.2, 74.7 and 51.1%, respectively), and central mudminnow were caught and tagged mostly in Main (58.5%). The minimum length of fish detected corresponded with the minimum length tagged for all the species that were detected. A total of 299 fish were detected on the stationary PIT array alone (26.3%); however, the average number of fish detected per day was 0.5% (ranged from 0 to 4.7%; Fig. 2).

Movement

The directional movements of creek chub varied among the reaches across seasons, with the greatest mean percentage of movements occurring into Kizell during the fall and spring (Kruskal–Wallis, $H = 11.90$, $df = 5$, $P = 0.04$; $H = 11.10$, $df = 5$, $P = 0.05$, respectively; Fig. 3A). The Kruskal–Wallis test for winter suggested a significant difference in movements of creek chub among reaches ($H = 11.43$, $df = 5$, $P = 0.04$); however, post-hoc comparisons (Tukey HSD) revealed no significant differences among reaches. Central mudminnow moved significantly more often from Watts into Kizell than from Kizell into Main during the fall (Kruskal–Wallis, $H = 12.94$, $df = 5$, $P = 0.02$; Fig. 3B), while there was no significant difference during summer and spring (sample size was too small for analysis in winter). Due to low sample sizes, only one analysis was

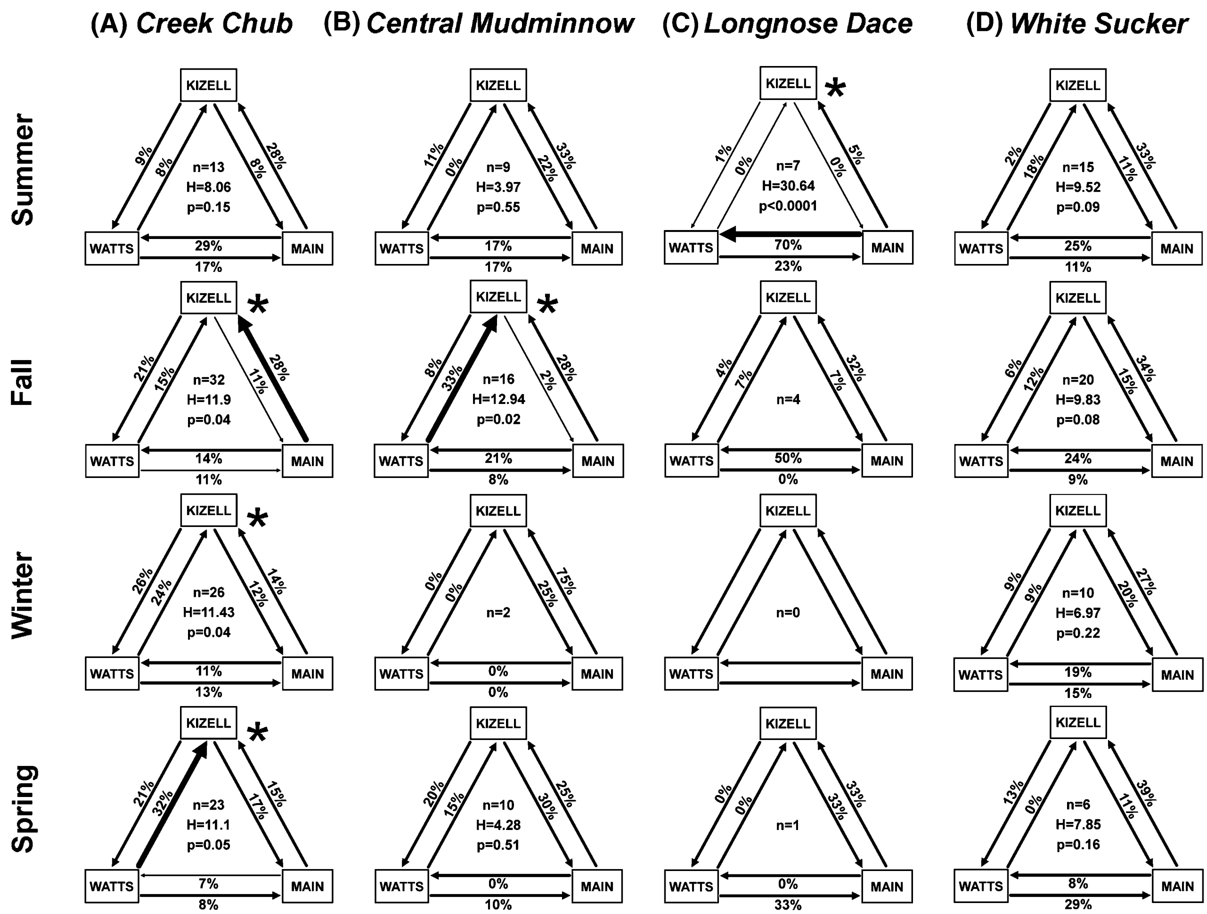


Fig. 3 Percentage of movement among reaches for **A** creek chub, **B** central mudminnow, **C** longnose dace, and **D** white sucker and across the seasons. Each percentage is the average proportion of movement for that species/season in that given direction. In the middle of each diagram is the sample size (n) and results of the Kruskal–Wallis analysis of variance. Degrees of freedom = 5 for all tests, and statistical significance ($P < 0.05$) is identified with (*asterisk*). For tests with significant results, the lines in the direction with the greatest or least movement are thicker or thinner, respectively

performed for longnose dace, which resulted in a significantly greater percentage of movement from Main into Watts relative to all other directions during the summer (Kruskal–Wallis, $H = 30.64$, $df = 5$, $P < 0.0001$; Fig. 3C). In contrast, the movements of white sucker were not significantly different among reaches during any season (Fig. 3D).

In terms of diel movement, creek chub and white suckers were detected at every hour of the day (Fig. 4), and while there was no discernable diel pattern for creek chub, there were slightly fewer records for white sucker mid-day. In contrast, almost all records for central mudminnow and longnose dace occurred between 6 pm and 6am (i.e. nocturnal activity).

Residency

A Kruskal–Wallis test on the residency of creek chub and longnose dace demonstrated a clear difference among reaches with significantly longer residency times in Watts than Kizell and Main (Kruskal–Wallis, $H = 56.64$, $df = 2$, $P < 0.0001$; $H = 114.66$, $df = 2$, $P < 0.0001$, respectively; Fig. 5). In contrast, central mudminnow spent significantly more time in both Kizell and Main than in Watts (Kruskal–Wallis, $H = 15.18$, $df = 2$, $P < 0.001$). Lastly, there were no differences in residency among reaches for white suckers (Kruskal–Wallis, $H = 0.25$, $df = 2$, $P = 0.88$).

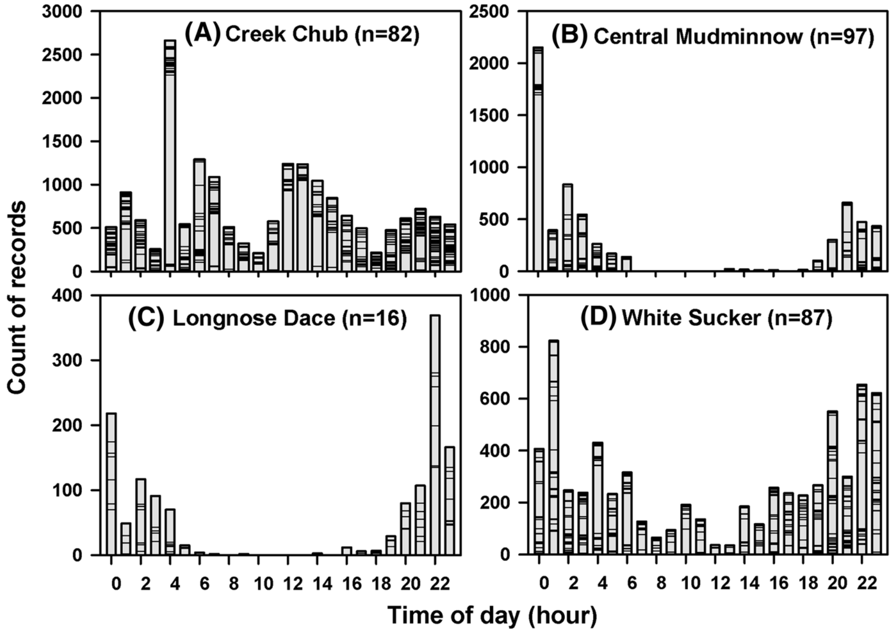


Fig. 4 Diel records (detections) for **A** creek chub, **B** central mudminnow, **C** longnose dace, and **D** white sucker over the entire study period. *Stacked bars* show the relative contributions of individuals. Note that the scale differs on the *y*-axis

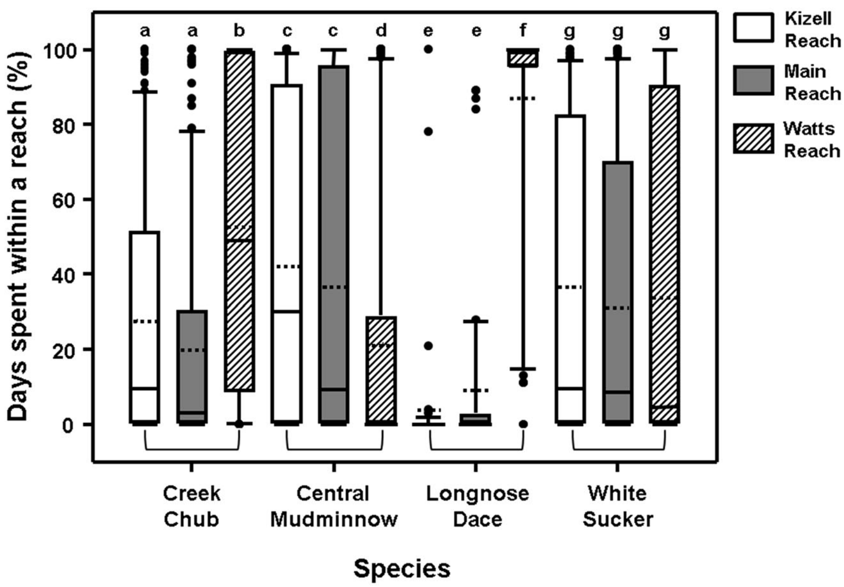


Fig. 5 Box-plots outlining the residency (percentage of days spent) within each reach for creek chub ($n = 120$), central mudminnow ($n = 115$), longnose dace ($n = 55$), and white sucker ($n = 104$). Degrees of freedom = 2 for all tests, and residency times that differed significantly ($P < 0.05$) between reaches are indicated by a *different letter*. The mean and median percentages of days are represented by the *dashed line* and *solid lines*, respectively. The lower and upper boundaries of the *boxes* represent the 25th and 75th percentiles, respectively. The whiskers (*error bars*) are the 10th and 90th percentiles, and outliers are shown as points

Discussion

Movement of stream fish

To our knowledge, this is the first study to evaluate the movements of stream fish between an earthen surface stormwater drain and urban stream including over winter months in a north temperate urban system. Given the degraded nature of the Kizell Drain, we had predicted fish would move proportionally less into this reach. Contrary to this prediction, we found a relatively high percentage of movements into Kizell throughout the year for white sucker (though not significantly different from other reaches), with creek chub and central mudminnow only showing differential reach use in some seasons (Fig. 3). The overall movement patterns for creek chub, central mudminnow and white sucker strongly suggest a high level of connectivity between Kizell Drain and Watts Creek, because fish moved quite freely between the two systems. However, it should be noted that Kizell had not been cleaned (with heavy equipment) in more than 10 years preceding this study and so it is possible that these results could differ depending on the duration since the last cleaning. Some studies have suggested that the short-term impacts of drainage work and maintenance result in reduced presence of fish populations (Swales, 1982; Meyer & Hinrichs, 2000), while Stammler et al. (2008) demonstrated that drain maintenance may not have a strong, lasting effect on fish assemblages. Nevertheless, the impacts of drain maintenance on fish could be species-specific and depend on the region and work being conducted. Thus, further research is necessary to better understand the short-term and long-term response of fish to cleaning activities within stormwater drains. Longnose dace was the only species that fit the prediction with proportionally less movement into Kizell (Fig. 3C); however, the sample sizes for dace were small preventing statistical analysis. Since dace were almost exclusively tagged in Watts and Main, an absence of movements into Kizell could be linked to homing behaviour. However, in a displacement study in the same system, longnose dace were found to actively and rapidly move out of Kizell Drain into Watts or Main, suggesting that it is indeed the degraded nature of Kizell that is precluding use by longnose dace (Crawford, 2014).

Winter was particularly interesting because of the lack of significant differences in movement among reaches for creek chub (according to post-hoc comparisons) and white sucker (Fig. 3A, D). Overwintering areas are generally understood to have suitable in-stream cover and increased habitat volume with reduced velocity (Schlosser, 1991; Cunjak, 1996); however, Kizell is predominantly shallow (<30 cm) with minimal in-stream cover (Maarschalk-Bliss, 2014). Although most winter research has focused on salmonids, Moshenko and Gee (1973) also described the overwintering habitat for creek chub as deep (>50 cm) sheltered pools. There are a few pools in Kizell that fit this description, and so it is possible that fish moving into Kizell could have exploited the few areas that were suitable for overwintering; however, the quantity and quality of overwintering habitats in drains would need to be further investigated. It is also possible that some fish use Kizell as a refuge from winter related changes such as ice build-up or break-up and winter floods. Brown et al. (2001) demonstrated that white sucker would move long distances in response to winter flooding and ice break-up. Whether fish were moving into Kizell to utilize habitat or in response to changes in the condition of habitats in Main or Watts is unknown. Regardless, this study demonstrates that earthen surface drains are capable of supporting different fish species throughout the year, including during winter.

Diel activity of stream fish is highly variable and complex both within and among species driven by external variables such as season, prey availability or predator avoidance (Reebs, 2002). In this study, the variability in diel detection patterns among creek chub, central mudminnow, longnose dace and white sucker further supports the importance of understanding species-specific patterns. Creek chub exhibited no clear diel pattern, while longnose dace and central mudminnow were more active at night (Fig. 4). Finally, while white sucker had slightly more detections at night they were detected to some extent at all times of the day. In contrast to the current findings, Reebs et al. (1995) found juvenile white suckers were more active during the day than at night. Steffensen et al. (2013) found that creek chub and white sucker move actively through a nature-like fishway almost exclusively overnight. Therefore, among the results of these two studies and the current study, three different diel behavioural patterns have been reported for white suckers suggesting that diel patterns not only vary across species but also within a species. This emphasizes the need to monitor movement over 24-h with technologies such as PIT telemetry so that different diel behaviours can be incorporated into the overall evaluation of stream fish movements.

Residency patterns of stream fish

It is increasingly apparent that stream fish populations are composed of sedentary and mobile individuals (Gatz & Adams, 1994; Hilderbrand & Kershner, 2000; Knaepkens et al., 2004) or even individuals that may switch between these behavioural modes (Harcup et al., 1984; Knaepkens et al., 2004). Furthermore, it has been suggested that some fish move to explore new habitats (Crook, 2004) due to resource variability or post-disturbance recolonization (Peterson & Bayley, 1993; Anderson & Quinn, 2006). This could partially explain the movement dynamics and spatial ecology of the fish populations within the Watts Creek watershed. Our movement analysis represented the mobile individuals of each species, while our residency analysis accounted for fish that were either sedentary or did not move far enough to be detected by the array. We observed that the residency of creek chub, central mudminnow, longnose dace and white sucker varied greatly among the reaches. Creek chub most often resided within Watts (Fig. 5), but displayed a fairly high percentage of movements into Kizell (Fig. 3A). Since creek chub were primarily found in Watts, individuals that moved into Kizell could be exploring to find new habitat or new resources. Longnose dace, on the other hand, clearly preferred Watts and spent little time in Kizell (Fig. 5). Given the strong association between longnose dace and riffle habitat (Gibsons & Gee, 1972), their avoidance of Kizell could be linked to an absence of appropriate habitat. Conversely, central mudminnow resided significantly longer in Kizell and Main likely because they specialize in habitats with low-flow, muddy bottoms and are subject to hypoxia (Martin-Bergmann & Gee, 1985). White sucker appear to be habitat generalists that prefer pool/run habitats and are tolerant of warm and low-flow environments (Vadas, Jr & Orth, 2000; Zorn et al., 2002), which explains their almost equal residency time among the reaches (Fig. 5). Considering that Kizell, like many other surface drains, was likely a natural waterway prior to conversion into drainage infrastructure, it is possible that the residency patterns of central mudminnow and white sucker included Kizell before it was altered into a drain. Another possible explanation is that some fish moved into Kizell after disturbances (e.g. the presence of a predator or resource depletion) and were able to colonize the area over time. Either way this demonstrates that some species are able to utilize resources and habitats, and therefore reside, within Kizell Drain.

Management implications

Movement is costly to fish due to energy expenditure (Boisclair & Tang, 1993) and the risk of predation (Belica & Rahel, 2008). As a result, fish tend to avoid habitats that do not provide energetic gains (Facey & Grossman, 1992). Therefore, our observation that creek chub, central mudminnow and white sucker are moving into and residing to some extent within Kizell suggests these fishes are gaining something from the habitat in Kizell (e.g. foraging, overwintering or spawning habitat). So, in urban environments where habitat degradation and loss is quite prominent, earthen stormwater drains could provide additional habitat that fish can exploit and eventually colonize. Stammler et al. (2008) demonstrated that fish colonize agricultural surface drains resulting in similar assemblages as local streams. Similarly, the current study suggests that urban surface drains need to be considered a part of and connected to the aquatic ecosystem that they drain into. Furthermore, the inclusion of surface drains will increase targeted home ranges and account for complex movement behaviours of some fish species (Smithson & Johnston, 1999). In summary, this study provides strong evidence that the management of urban aquatic ecosystems needs to consider earthen surface stormwater drains as a functional component of urban watersheds to reflect their value as fish habitat.

Acknowledgments For field assistance, we are grateful to A. Muhametsafina, E. Samson, S. Bower, T. Prystay, other members of the Fish Ecology and Conservation Physiology Laboratory, and M. Caputo from the National Capital Commission. We thank the Ontario Ministry of Natural Resources and the National Capital Commission for kindly providing research permits. Project funding was provided primarily by the National Capital Commission, while additional support was through the Fish Ecology and Conservation Physiology Laboratory (S.J.C.) via NSERC and the Canada Research Chairs program. S.M. Bliss was supported by an Ontario Graduate Scholarship from the Province of Ontario and Carleton University. This project was conducted in accordance with the guidelines of the Canadian Council on Animal Care administered by the Carleton University Animal Care Committee (B10-12). We thank several anonymous referees for providing thoughtful comments on our manuscript.

References

Aarestrup, K., M. C. Lucas & J. A. Hanson, 2003. Efficiency of a nature-like bypass channel for sea trout (*Salmo trutta*) ascending a small Danish stream studied by PIT telemetry. Ecology of Freshwater Fish 12: 160–168.

Anderson, J. H. & T. P. Quinn, 2006. Movement of adult coho salmon (*Oncorhynchus kisutch*) during colonization of newly accessible habitat. Canadian Journal of Fisheries and Aquatic Sciences 64: 1143–1154.

Aymes, J. C. & J. Rives, 2009. Detection efficiency of multiplexed Passive Integrated Transponder antennas is influenced by environmental conditions and fish swimming behaviour. Ecology of Freshwater Fish 18: 507–513.

Belanger, G. & M. Rodriguez, 2002. Local movement as a measure of habitat quality in stream salmonids. Environmental Biology of Fishes 64: 155–164.

Belica, L. A. T. & F. J. Rahel, 2008. Movements of creek chubs, *Semotilus atromaculatus*, among habitat patches in a plains stream. Ecology of Freshwater Fish 17: 258–272.

Berkman, H. E. & C. F. Rabeni, 1987. Effect of siltation on stream fish communities. Environmental Biology of Fishes 18: 285–294.

Boisclair, D. & M. Tang, 1993. Empirical analysis of the influence of swimming pattern on the net energy cost of swimming in fishes. Journal of Fish Biology 42: 169–183.

Brown, R. S., G. Power & S. Beltaos, 2001. Winter movements and habitat use of riverine brown trout, white sucker and common carp in relation to flooding and ice break-up. Journal of Fish Biology 59: 1126–1141.

Brown, R., W. Hubert & S. Daly, 2011. A primer on winter, ice, and fish: what fisheries biologists should know about winter ice processes and stream-dwelling fish. Fisheries 36: 8–26.

Burnett, N. J., K. M. Stamplecoskie, J. D. Thiem & S. J. Cooke, 2013. Comparison of detection efficiency among three sizes of half-duplex passive integrated transponders using manual tracking and fixed antenna arrays. North American Journal of Fisheries Management 33: 7–13.

Coker, G. A., C. B. Portt & C. K. Minns, 2001. Morphological and ecological characteristics of Canadian freshwater fishes. Report to Fisheries and Oceans Canada, Burlington.

Cookingham, M. N. & C. R. Ruetz III, 2008. Evaluating passive integrated transponder tags for tracking movements of round gobies. Ecology of Freshwater Fish 17: 303–311.

Crawford, C., 2014. Experimental displacement of individual longnose dace (*Rhinichthys cataractae*) tagged with passive integrated transponders reveals fish avoidance of a stormwater drain in an urban watershed. Undergraduate Thesis, Institute of Environmental Science, Carleton University, Ottawa ON.

Crook, D. A., 2004. In the home range concept compatible with the movements of two species of lowland river fish? Journal of Animal Ecology 73: 353–366.

Cucherousset, J., J. R. Britton, W. R. Beaumont, M. Nyqvist, K. Sievers & R. E. Gozlan, 2010. Determining the effects of species, environmental conditions and tracking method on the detection efficiency of portable PIT telemetry. Journal of Fish Biology 76: 1039–1045.

Cunjak, R. A., 1996. Winter habitat of selected stream fishes and potential impacts from land-use activity. Canadian Journal of Fisheries and Aquatic Sciences 53: 267–282.

Dieterman, D. J. & J. H. Hoxmeier, 2011. Instream evaluation of passive integrated transponder retention in brook trout: effects of season, anatomical placement, and fish length. North American Journal of Fisheries Management 29: 109–115.

Djokic, D. & D. R. Maidment, 1991. Terrain analysis for urban stormwater modelling. Hydrological Processes 5: 115–124.

Facey, D. E. & G. D. Grossman, 1992. The relationship between water velocity, energetic costs, and microhabitat use in four North American stream fishes. Hydrobiologia 239: 1–6.

Freeman, M., 1995. Movements by two small fishes in a large stream. Copeia 1995: 361–367.

Funk, J. L., 1957. Movement of stream fishes in Missouri. Transactions of the American Fisheries Society 85: 39–57.

Gatz, A. J. & S. M. Adams, 1994. Patterns of movement of centrarchids in two warmwater streams in eastern Tennessee. Ecology of Freshwater Fish 3: 35–48.

Gibbons, J. W. & K. M. Andrews, 2004. PIT tagging: simple technology at its best. BioScience 54: 447–454.

Gibsons, J. R. & J. H. Gee, 1972. Ecological segregation between longnose and blacknose dace (Genus *Rhinichthys*) in the Mink River, Manitoba. Journal of Fisheries Research Board of Canada 29: 1245–1252.

Goldstein, R. M. & M. R. Meador, 2005. Multilevel assessment of fish species traits to evaluate habitat degradation in streams of the upper Midwest. North American Journal of Fisheries Management 25: 180–194.

Harcup, M. F., R. Williams & D. M. Ellis, 1984. Movements of brown trout, *Salmo trutta L.*, in the river Gwyddon, South Wales. Journal of Fish Biology 24: 415–426.

Hatt, B. E., T. D. Fletcher, C. J. Walsh & S. L. Taylor, 2004. The influence of urban density and drainage infrastructure on the concentrations and loads of pollutants in small streams. Environmental Management 34: 112–124.

Hilderbrand, R. H. & J. L. Kershner, 2000. Movement patterns of stream-resident cutthroat trout in Beaver Creek, Idaho-Utah. Transactions of the American Fisheries Society 129: 1160–1170.

Kaushal, S. S. & K. T. Belt, 2012. The urban watershed continuum: evolving spatial and temporal dimensions. Urban Ecosystems 15: 409–435.

Klein, R., 1979. Urbanization and stream quality impairment. Journal of the American Water Resources 15: 948–963.

Knaepkens, G., L. Bruyndoncx & M. Eens, 2004. Assessment of residency and movement of the endangered bullhead (*Cottus gobio*) in two Flemish rivers. Ecology of Freshwater Fish 13: 317–322.

Lucas, M. C. & E. Baras, 2000. Methods for studying spatial behaviour of freshwater fishes in the natural environment. Fish and Fisheries 1: 283–316.

Maarschalk-Bliss, S. M., 2014. Seasonal variation in assemblage structure and movement of small stream fish in an urban environment. Master of Science Thesis, Department of Biology, Carleton University, Ottawa ON.

Marchetti, M. & P. Moyle, 2001. Effects of flow regime on fish assemblages in a regulated California stream. Ecological Applications 11: 530–539.

Martin-Bergmann, K. A. & J. H. Gee, 1985. The central mudminnow, *Umbra limi* (Kirtland), a habitat specialist and resource generalist. Canadian Journal of Zoology 63: 1753–1764.

McEwan, A. J. & M. K. Joy, 2011. Monitoring a New Zealand freshwater fish community using passive integrated transponder (PIT) technology; lessons learned and recommendations for future use. New Zealand Journals of Marine and Freshwater Research 45: 121–133.

Meyer, L. & D. Hinrichs, 2000. Microhabitat preferences and movements of the weatherfish, *Misgurnus fossilis*, in a drainage channel. Environmental Biology of Fishes 58: 297–306.

Moshenko, R. W. & J. H. Gee, 1973. Diet, time, and place of spawning, and environments occupied by creek chub (*Semotilus atromaculatus*) in the Mink River, Manitoba. Journal of the Fisheries Research Board of Canada 30: 357–362.

Norman, J., M. Hagler & M. Freeman, 2009. Application of a multistate model to estimate culvert effects on movement of small fishes. Transactions of the American Fisheries Society 138: 826–838.

Paul, M. & J. Meyer, 2001. Streams in the urban landscape. Annual Review of Ecology and Systematics 32: 333–365.

Peterson, J. T. & P. B. Bayley, 1993. Colonization rates of fishes in experimentally defaunated warmwater streams. Transactions of the American Fisheries Society 122: 199–207.

Puth, L. M. & K. A. Wilson, 2001. Boundaries and corridors as a continuum of ecological flow control: Lessons from rivers and streams. Conservation Biology 15: 21–30.

Reebs, S. G., L. Boudreau, P. Hardle & R. A. Cunjak, 1995. Diel activity patterns of lake chubs and other fishes in a temperate stream. Canadian Journal of Zoology 73: 1221–1227.

Reebs, S. G., 2002. Plasticity of diel and circadian activity rhythms in fishes. Reviews in Fish Biology and Fisheries 12: 349–371.

Rodriguez, M. A., 2002. Restricted movement in stream fish: the paradigm is incomplete, not lost. Ecology 83: 1–13.

Roussel, J., R. A. Cunjak, R. Newbury, D. Caissie & A. Haro, 2004. Movement and habitat use by PIT-tagged Atlantic salmon parr in early winter: the influence of anchor ice. Freshwater Biology 49: 1026–1035.

Roy, A. H., S. J. Wenger, T. D. Fletcher, C. J. Walsh, A. R. Ladson, W. D. Shuster, H. W. Thurston & R. R. Brown, 2008. Impediments and solutions to sustainable, watershed-scale urban stormwater management: lessons from Australia and the United States. Environmental Management 42: 344–359.

Schlosser, I., 1991. Stream fish ecology: a landscape perspective. BioScience 41: 704–712.

Scott, J., C. Steward & Q. Stober, 1986. Effects of urban development on fish population dynamics in Kelsey Creek, Washington. Transactions of the American Fisheries Society 115: 555–567.

Scott, W. B. & E. J. Crossman, 1998. Freshwater Fishes of Canada. Fisheries Research Board of Canada Bulletin, 184.

Smithson, E. B. & C. E. Johnston, 1999. Movement patterns of stream fishes in an Ouachita Highlands stream: an examination of the restricted movement paradigm. Transactions of the American Fisheries Society 128: 847–853.

Sponseller, R., E. Benfield & H. Valett, 2001. Relationships between land use, spatial scale and stream macroinvertebrate communities. Freshwater Biology 46: 1409–1424.

Stammler, K. L., R. L. McLaughlin & N. E. Mandrak, 2008. Streams modified for drainage provide fish habitat in agricultural areas. Canadian Journal of Fisheries and Aquatic Sciences 65: 509–522.

Steffensen, S. M., J. D. Thiem, K. M. Stamplecoskie, T. R. Binder, C. Hatry, N. Langlois-Anderson & S. J. Cooke, 2013. Biological effectiveness of an inexpensive nature-like fishway for passage of warmwater fish in a small Ontario stream. Ecology of Freshwater Fish 22: 374–383.

Swales, S., 1982. A 'before and after' study of the effects of land drainage works on fish stocks in the upper reaches of a lowland river. Fisheries Management 13: 105–114.

Teixeira, A. & R. M. V. Cortes, 2007. PIT telemetry as a method to study the habitat requirements of fish populations: application to native and stocked trout movements. Hydrobiologia 582: 171–185.

Vadas Jr, R. L. & D. J. Orth, 2000. Habitat use of fish communities in a Virginia stream system. Environmental Biology of Fishes 59: 253–269.

Walsh, C., A. Roy, J. Feminella, P. Cottingham, P. Groffman & R. Morgan II, 2005. The urban stream syndrome: current knowledge and the search for a cure. Journal of North American Benthological Society 24: 706–723.

Wichert, G. & D. Rapport, 1998. Fish community structure as a measure of degradation and rehabilitation of riparian systems in an agricultural drainage basin. Environmental Management 22: 425–443.

Zorn, T. G., P. W. Seelbach & M. J. Wiley, 2002. Distributions of stream fishes and their relationships to stream size and hydrology in Michigan's lower peninsula. Transactions of the American Fisheries Society 131: 70–85.

Zydlewski, G. B., A. Haro, K. G. Whalen & S. D. McCormick, 2001. Performance of stationary and portable passive transponder detection systems for monitoring of fish movements. Journal of Fish Biology 58: 1471–1475.

Zydlewski, G. B., G. Horton, T. Dubreuil, B. Letcher, S. Casey & J. Zydlewski, 2006. Remote monitoring of fish in small streams. Fisheries 31: 492–502.