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Measuring 30 years of improvements to aquatic connectivity in the Greater Toronto Area

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Instream barriers (e.g. dams, weirs and road crossings) fragment aquatic habitat and prevent the upstream movement of fish, impairing the ability of fishes to complete critical life stages, access critical habitat and for dispersal among local populations. Mitigation efforts have improved aquatic connectivity to some degree, but it has been challenging to quantify the overall improvement in connectivity without long-term and costly field assessments. The development of spatially explicit habitat connectivity indices make it possible to evaluate current stream connectivity, and quantify the improvement prior mitigation projects have had on connectivity. We combined a list of instream barrier mitigation projects completed in five watersheds in the Toronto (Ontario, Canada) area from 1987–2016 (mitigated barriers) and a previously established inventory of all known instream barriers in 2016 (current barriers). The cumulative improvement to connectivity was measured for potadromous (remain in tributaries) and diadromous (move between tributaries and lake) fish species using the dendritic connectivity index. Aquatic connectivity improved for diadromous species between 0 and 14.5% and for potadromous species between 0.1 and 4.4% in the five studied watersheds. Some variation in improvement among the watersheds can likely be attributed to differences in mitigation strategies among the watersheds and a historical emphasis on mitigating instream barriers to benefit migratory salmonid species.

Keywords: instream barrier mitigation, stream fragmentation, dendritic connectivity index, urban stream, fish passage

Introduction

Anthropogenic development has altered many waterways through habitat degradation, water pollution, over-exploitation, the establishment of invasive species and habitat fragmentation (Dudgeon et al., 2006; Strayer and Dudgeon, 2010). The alteration of habitat has in turn resulted in a decline in freshwater biodiversity, particularly in areas where intensive urban development has occurred (Porto et al., 1999; Bunn and Arthington, 2002; Beatty et al., 2013). The construction of instream barriers is ubiquitous in urban areas and these barriers alter flow regimes and prevent the movement of organisms among different sections of the stream (Porto et al., 1999; Bunn and Arthington, 2002; Beatty et al., 2013). Dams, weirs, and road crossings provide valuable services, but they also fragment aquatic habitats and have negative impacts on

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fishes (Dynesius and Nilsson, 1994; Trombulak and Frissel, 2000; Rolls et al., 2013).

Habitat fragmentation limits the amount of suitable habitat available for fishes, resulting in a higher likelihood that critical stream segments become inaccessible (Trombulak and Frissell, 2000). The elimination of movement between upstream and downstream populations can rapidly alter fish communities (Gehrke et al., 2002; Nilsson et al., 2005; Nislow et al., 2011; Rolls et al., 2013; Maitland et al., 2016) through increased community dissimilarity and the isolation of populations (Hanfling et al., 2004; Perkin and Gido, 2012; Edge et al., 2017). Diadromous and potadromous fishes are susceptible to fragmentation, as many of these fish species need to move among different habitat types to meet critical biological functions (Lucas et al., 2001). The creation of instream barriers also changes stream morphology, altering flow patterns and substrate composition (Lucas et al., 2001; Bunn and Arthington, 2002; Maitland et al., 2016). Overall, the construction of instream barriers has led to a rapid deterioration of habitat quality and quantity and mitigating instream barriers has become a main focus in recent aquatic restoration efforts (Roni et al., 2002; Bernhardt et al., 2005; O'Hanley and Tomberlin, 2005).

The Great Lakes system of North America contains 23,000 km^3 of freshwater and is the largest group of freshwater lakes on our planet (Hales et al., 2008). There are an estimated 270,000 potential barriers within the Great Lakes tributaries, with over 45 large dams and thousands of road crossings documented in the Greater Toronto Area (GTA) alone (Januchowski-Hartley et al., 2013; Ontario Biodiversity Council, 2016). The threats of instream barriers to aquatic communities have been recognized in the development of the Toronto and Region Remedial Action Plan (RAP) (Toronto RAP, 2016). A significant amount of work has been done over the past three decades to mitigate instream barriers in the GTA. The removal of instream barriers can restore ecological communities at local sites (Doyle et al., 2005; Gardner et al., 2011), but the extent of improvement to aquatic connectivity has been traditionally difficult to assess quantitatively (Beatty et al., 2013; Rolls et al., 2013) because of the large spatial extent of rivers. To fill this gap, tools to estimate improvement to connectivity after mitigation have been developed to more effectively prioritize the removal of instream barriers by estimating the amount of upstream habitat that becomes available if a barrier is migrated (e.g. "Fishwerks," Moody et al., 2017). An additional piece of information is the degree to which the connectivity of the entire habitat network is improved as it provides a measure of how well all segments of the habitat network are connected to one another. The development of spatially explicit habitat connectivity indices such as the Dendritic Connectivity Index (DCI; Cote et al., 2009) allow for network level assessments of connectivity to be made and provide a valuable metric that can be used to quantify the structural connectivity within river networks. The DCI metric can be calculated for both diadromous and potadromous species and can be compared between watersheds or different time frames, resulting in a method to compare the connectedness of different watersheds and to assess changes in aquatic connectivity over time (Cote et al., 2009).

The objective of our project was to quantify the improvement to aquatic connectivity within the GTA since the inception of the Toronto RAP for both diadromous and potadromous species. We compared connectivity levels in 1987 (before the RAP recommended barrier mitigation projects) and in 2016 (after barrier mitigation efforts took place). We expected the connectivity for diadromous species to improve to a greater extent for potadromous species because past restoration efforts likely focused on migratory salmonids species and that more mitigation projects will be found in streams used by salmon.

Methodology

Study site

The present study focusses on five of the six watersheds within the Toronto and Region Area of Concern in Ontario, Canada (43.7° N, 79.4° W); the East Don River, Etobicoke Creek, Highland Creek, Mimico Creek, and Rouge River (Figure 1) and does not study the West Don River or the Humber River. Each of the five watersheds has been fragmented by varying degrees due to the construction of dams, weirs, road crossings, and other instream structures and these watersheds vary in size, percent impervious cover, and the percent of natural cover (Table 1). The Don River, Rouge River, and Etobicoke Creek watersheds are

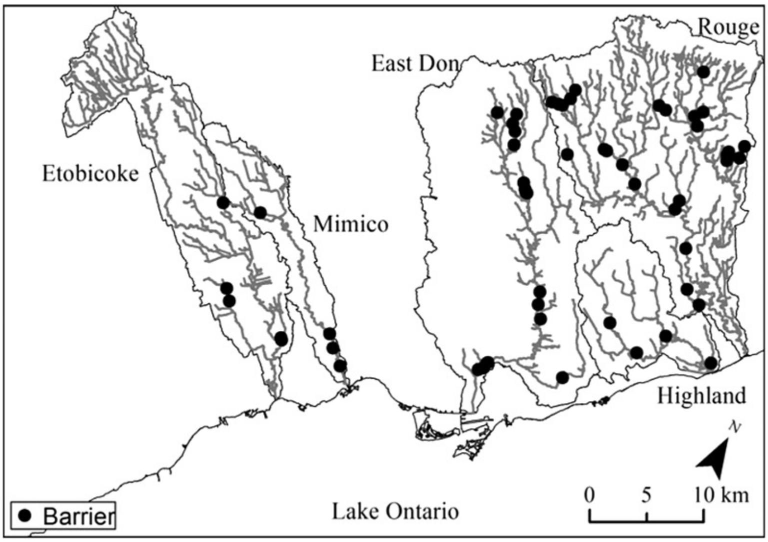

Figure 1. Location of barrier mitigation projects in the five focal watersheds which occurred between 1987 and 2016.

Table 1 General characteristics of the five watersheds in Southern Ontario and the number of barriers in each watershed in 1987 vs. 2016.

Watershed	Length of river (km)	Watershed area (ha)	Natural cover (%)	Percent impervious cover (%)	Number of barriers in 1987	Number of barriers in 2016
East Don	194.2	35806	14	19-31	79	64
Etobicoke	279.8	21165	14	7-62	190	181
Highland	78.1	10158	11	53	143	139
Mimico	68.9	7709	11	57	154	152
Rouge	541.8	33288	23	4-50	207	194

heavily urbanized near their mouths and less urbanized in the headwaters (PIC <10%). In contrast, the Highland and Mimico watersheds are heavily urbanized throughout.

Complete barrier assessment

Complete barrier assessments were completed for the five watersheds between 2002 and 2016 and represent the current number and type of barriers in each of the watersheds. Barrier assessments consisted of walking the entire stream network and recording the location and type (e.g. dam, weir, road crossing) of every potential barrier to fish passage. Barrier characterization included measuring downstream pool depth, the distance from the lip of the barrier to the stream bed, the distance from the lip of the barrier to the top of the waterline, and the hydraulic head of each barrier. The pool depth and barrier height were used to determine whether the lip of the crossing structure was above the surface of the water, resulting in a drop structure or perched condition.

Instream barrier mitigation project list

We identified previously mitigated instream barriers by contacting groups and agencies (e.g. Trout Unlimited, Ontario Streams, Ontario Ministry of Natural Resources, Department of Fisheries and Oceans) that were historically involved with mitigation projects in the GTA. The following minimum information was requested for each project: (1) Where the project was located and a description of the area, (2) UTM coordinates if available, (3) Year(s) of project execution, (4) Structure classification of the instream barrier pre-mitigation effort (e.g. dam, debris, natural barrier, road crossing, weir) and (5) Mitigation method used (e.g. bypass, fishway, notch, removal, rocky ramp). Instream barrier mitigation projects were also found by reviewing prior permit applications under Ontario Regulation 166/06 in the Fisheries and Oceans Canada database and TRCA corporate records database.

Some of the completed barrier mitigation projects had the possibility of degrading over time (e.g. a blocked bypass channel). To accurately assess the current level of aquatic connectivity past barrier mitigation project sites were visited when they met all of the following conditions: (1) The project was located in one of the five watersheds that had a complete barrier assessment, (2) The mitigation project took place before 2011 and there were no photographic records or documents confirming project completion and (3) The barrier could not be confirmed as mitigated via LiDAR Hillshade and Elevation layers or Google Earth's historical satellite photographs. Site visits to assess current conditions at instream barrier mitigation sites were done in low flow conditions in August-September 2016 and assessed for three categories of fish passage: (1) No species passage, (2) All species passage and (3) Only jumping species passage. If flow was continual, not sheeting over or through the structure, and the stream elevation change was less than 5 cm, it was determined that all fish species could pass. If a site was identified as allowing no species or only jumping species passage the barrier was measured and characterized using the same methods as the complete barrier assessment.

Aquatic connectivity

Structural connectivity was measured using the Dendritic Connectivity Index (Cote et al., 2009). The DCI estimates the probability that any two organisms placed randomly in two different stream segments are in sections that are structurally connected to one another. DCI was calculated for both diadromous, species that move between Lake Ontario and its tributaries (DCId) and potadromous, species that remain in the tributaries (DCIp) fishes, as well as for each individual stream segment (DCIs). The DCIs value estimates the probability that any particular stream segment is connected to the rest of the network and can be used to indicate the degree to which individual stream segments are connected to one another. The permeability of each barrier was estimated using baseflow, measured as part of a regional monitoring program, and perch height measured during barrier assessments (Table 2).

Improvement to connectivity in each of the watersheds was determined by calculating DCIp, DCId, and DCIs for 1987 and 2016. To calculate the connectivity indices in 1987 all barriers (barrier assessment and mitigated barrier list) were included with all barriers on the mitigated list assigned a permeability of 0. To calculate the connectivity indices in 2016 the permeability value for the mitigated barriers was changed to match the permeability after mitigation.

Statistical analysis

For each of DCIp and DCId, we tested whether connectivity improved between 1987 and 2016 using a paired t-test for each of the connectivity indices. We also tested whether the improvement in connectivity differed between diadromous and potadromous species by comparing the difference between 1987 and 2016 using a paired t-test. To test whether barrier mitigation projects were more likely to occur near the mouth of stream the density distribution of distance from barrier to mouth of the river was compared between mitigated and non-mitigated barriers. All statistics were performed in R (R Core Team, 2016).

Table 2. Categories used to estimate the permeability of each barrier.

Outlet drop (m)	Baseflow ($m\ s^{-1}$)	Estimated permeability
0	<0.25	1
0	0.25-0.40	0.80
0	>0.40	0.50
0-0.15	Any	0.25
>0.15	Any	0

Categories from Anderson et al. (2012)

Results

Instream barrier mitigation project list

A total of 173 instream barrier mitigation projects were identified in the GTA and 68 of these projects were completed in the five focal watersheds (Table 3; Figure 1). Within the five focal watersheds the majority of barrier mitigation projects occurred in the Rouge (27), and East Don (22). Weirs were the most commonly mitigated barrier (37), followed by road crossings (17) and dams (14) (Table 3). Total removal of the barrier (23) and the installation of rocky ramps (18) were the most common mitigation methods (Table 3). Density distributions show that the majority of instream barrier mitigation projects occurred close to the mouth in the East Don, Etobicoke, Mimico, and Rouge watersheds (Figure 2).

Aquatic connectivity–1987 vs. 2016

In 1987 DCId ranged between 2.17 and 8.03% and DCIp ranged between 2.75 and 4.92% in the five focal watersheds (Table 4). Both DCId and DCIp increased between 1987 and 2016, with DCId ranging between 2.17 and 22.51% and DCIp ranging between 2.84 and 9.32% (Table 4). The average improvement in DCId was 4.15% and DCIp was 1.19%. However the observed differences for DCId and DCIp between 1987 and 2016 were not statistically significant (DCId: $t = -1.45$, $df = 4$, $p = 0.22$; DCIp: $t = -1.43$, $df = 4$, $p = 0.22$), nor was the difference in improvement between DCId and DCIp ($t = -1.44$, $df = 4$, $p = 0.22$). The lack of statistical significance is likely to due to large amount of variation in improvement among the watersheds and low sample size. The greatest improvement in DCId occurred in the East Don (14.48%) and the Rouge (6.28%), but there was no improvement in the Etobicoke, Highland, and Mimico (Table 4). Similarly DCIp improved the most in the East Don (4.4%) and in the Rouge (1.2%) and there was an extremely minor improvement (<1%) in the Etobicoke, Highland, and Mimico (Table 4). Overall, aquatic connectivity for potadromous species improved in all watersheds from 1987 to 2016, but improved in only two out of the five watersheds for diadromous species.

Aquatic connectivity–Dendritic Connectivity Index

DCIs values for stream connectivity varied both among and within the five focal watersheds. The greatest improvement was in the East Don where DCIs for some stream segments improved by up to 22.5%. In the East Don there was a clear spatial pattern in local connectivity improvement; the greatest improvement was at the mouth and in one north-western portion of the stream (Figure 3a). DCIs values in the Rouge ranged from -8.2 to 10.9% and the greatest improvement occurred close to the mouth (Figure 3a). DCIs values in Etobicoke Creek showed some deterioration in connectivity with a low of -0.03% ranging to a high of 3.35% (Figure 3a). Negative DCIs values occur when the permeability of barriers decrease or when a new barrier is placed on the network, which occurred in both the Rouge and Etobicoke. Improvement in DCIs in Mimico

Table 3. The number of mitigated barriers, types of barriers mitigated, and what methods were used to mitigate barriers in the five measured watersheds.

		Types of barrier mitigated			Method used to mitigate barriers				
Watershed	Number	Road	Dam	Weir	Removal	Rocky Ramp	Replace	Bypass/fishway	Other
East Don	24	5	1	18	11	8	1	2	2
Etobicoke	9	1	4	4	5	1	0	0	3
Highland	4	1	0	3	2	1	0	0	1
Mimico	4	0	0	4	0	3	0	1	0
Rouge	27	10	9	8	5	5	5	12	0
Total	68	17	14	37	23	18	6	15	6

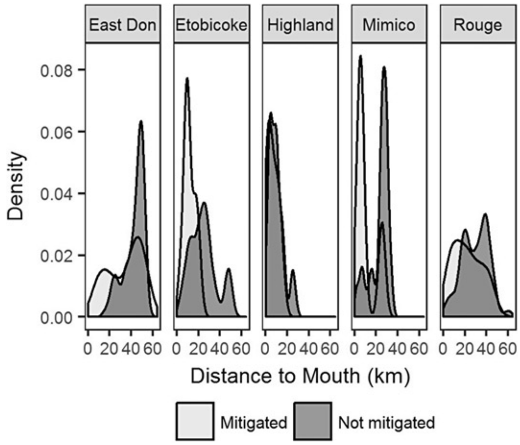

Figure 2. Density plot of distance from barriers to the mouth of the river (m) in five watersheds.

and Highland creeks were minimal, with the largest improvement ranging from 3.74 to 6.39% (Figure 3a). However, DCIs values in large portions of the Etobicoke, Mimico, and Highland did not change, with the increases in DCIs occurring in a small number of stream segments in close proximity to mitigated barriers. In 2016, the highest DCIs values were found near the mouths of the Mimico, East Don, and Rouge and in some upper tributaries of the East Don and Rouge (Figure 3b).

Discussion

The negative effects of instream barriers to fish communities are extensive and well documented (Morita and Yamamoto, 2002; Taylor et al., 2008; O'Hanley, 2011; Edge et al., 2017). Restoration actions have focused on mitigating instream barriers, but the extent of improvement in aquatic connectivity has traditionally been difficult to quantify. The objective of this study was to utilize a spatially explicit connectivity index to determine whether instream barrier mitigation projects have improved structural connectivity in five focal watersheds and where the greatest improvement has occurred. Our findings show that there have been improvements in each watershed, although the amount of improvement is not statistically significant. There is large variability in the amount of improvement among watersheds, with larger improvements in connectivity in the East Don and Rouge compared to Etobicoke, Highland, and Mimico creeks. Aquatic connectivity also improved considerably more for diadromous species than for potadromous species. The variation in improvement can likely be attributed to: the total number of completed mitigation projects in each watershed, conservation of high quality habitat, restoration of highly degraded habitat, and an emphasis on improving connectivity for migratory salmonids rather than resident species.

Differences in improvement among the watersheds are due to the different number of mitigation projects that were completed in each of the watersheds; more than 20 projects were completed in each of the East Don and Rouge watersheds, and less than 10 projects were completed in Etobicoke, Highland, and Mimico creeks. There is an expected, and obvious, positive relationship between the number of projects completed in a watershed and the consequent improvement in connectivity. We hypothesize that prior mitigation projects were concentrated in the East Don and Rouge rivers due to a focus on conservation or restoration depending on watershed condition in the GTA over the past 3 decades.

The Rouge River is considered one of the more pristine watersheds within the GTA and is of high conservation value. It has been well documented that urbanization is a major cause for aquatic habitat degradation (Booth and Jackson, 1997; Walsh et al., 2005). With extensive rural land cover (51%) and a low PIC in the northern reaches, the Rouge watershed still contains a large amount of natural land cover (Tu et al., 2010). Land cover characteristics which imply that more high quality habitat is available for fish species in comparison to other GTA watersheds that have considerably higher levels of urban land cover. The density distribution of mitigation projects and their distance from the mouth of the Rouge shows that a large proportion of projects were completed further upstream in the headwaters (Figure 2). Upstream areas in the Rouge have the lowest PIC and highest levels natural cover, lending support to the idea that instream barrier mitigation projects have targeted these relatively pristine habitats. The trend of mitigating instream barriers in areas with less urbanization shows a tendency for conservation efforts to be focused on relatively undisturbed areas. This approach has merit, as concentrating on stream segments with lower impact from urbanization

Table 4. DCI values for potadromous and diadromous species from 1987 (before the Toronto RAP) and 2016 in each of the five watersheds.

	DCI Diadromous (%)		DCI Potadromous (%)	
Watershed	1987	2016	1984	2016
East Don	8.03	22.51	4.92	9.32
Etobicoke	2.17	2.17	2.75	2.84
Highland	4.76	4.76	2.83	2.90
Mimico	3.13	3.13	4.73	4.93
Rouge	4.64	10.92	3.65	4.85

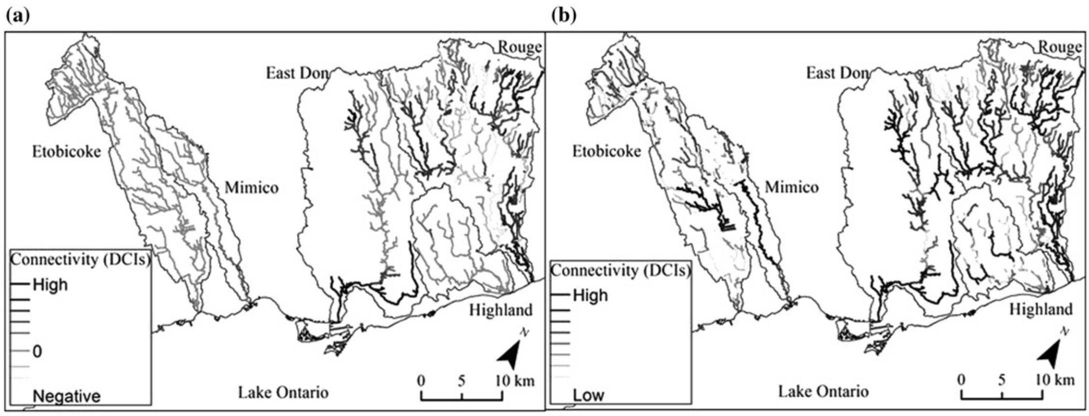

Figure 3. (a) Difference in stream connectivity (DCIs) between 2016 and 1987. Values are DCIs in 2016–DCIs in 1987, larger differences indicate greater improvement in connectivity between 1987 and 2016. (b) DCIs values for the five study watercourses in 2016 showing current conditions.

allows fishes access to higher quality habitat (Roni et al., 2002). Implementing projects in rural, relatively undisturbed areas may also be more cost efficient because the habitat may be of high quality in the area (Arponen et al., 2010). Whereas, in more degraded streams, extra costs will be incurred by further habitat restoration to improve habitat quality. Economic costs are one of the main limiting factors in the ability to complete restoration related projects, and sometimes the least expensive options are chosen for restoration due to limited funding available. By maximizing both economic efficiency and the largest biological gain in the conservation planning stages, decisions can be made to best benefit our aquatic communities (Arponen et al., 2010).

Contrasting the relatively pristine Rouge, the East Don watershed is dominated by urban land cover (97%) and is one of the most degraded rivers in the GTA (Mitchell, 2005). Despite evidence pointing towards a highly degraded system, 22 instream barrier mitigation projects have been completed in the East Don since 1987, with many of these projects being located close to the river mouth to restore connections to the lake. Past development practices in the Don River resulted in a dramatic decline habitat quality and prior to the RAP very little conservation value was left in the system (Mitchell, 2005; Bonnell, 2008). In the past few decades, intensive efforts have been made to assess and restore many aspects of aquatic health in the Don due to increased public and environmental awareness (Bonnell, 2008). An observable achievement of these restoration efforts has been the successful upstream migration of Chinook Salmon (*Oncorhynchus tshawytscha*) in the Don River. However, it is still not clear whether the available habitat is of high enough quality for spawning, embryo development, and juvenile growth to occur in the East Don (Crawford and Muir, 2008). Nevertheless, the presence of salmonids in the upper East Don demonstrates that mitigating instream barriers, even in heavily urbanized city centres can lead to successful restoration of habitat connectivity.

Improvement in aquatic connectivity for both diadromous and potadromous species was not statistically significant, but this is likely due to the small sample size ($n = 5$) and the three watersheds (i.e. Etobicoke, Highland, and Mimico creeks) that showed minimal improvement (<1%). However, the mean improvement in DCId increased fourfold when compared to the mean improvement in DCIp. A reason for this substantial difference in improvement can be attributed to the widespread emphasis on restoring migratory salmonid habitat (Metrick and Wetizman, 1998; Roni et al., 2002; Pess et al., 2014). Salmonids have long been the focus of many stream restoration projects due to the ecological, economic, and cultural repercussions associated with declining salmon runs (Gende et al., 2002). The instream barrier mitigation projects that have taken place in the Don River are a prime example of this salmonid focus. Almost half of the mitigated instream barriers in the East Don have been closer to the mouth of the river instead of being further up in the headwaters. Removing barriers at the mouth of a river will improve aquatic connectivity for all diadromous species, and potadromous species that only utilize the headwaters will not be affected. The DCIs metric identifies where connectivity has improved the most within a riverine system and segments near the mouth of the East Don have improved by over 20%, whereas the middle of the stream and the headwaters have only improved by less than 10%. The large improvement in connectivity at the mouth of the East Don supports the theory that restoration efforts have focused on salmonids. The same trend can be seen in the Rouge, with portions of the stream closer to the mouth having improved by the largest amount compared to the headwaters (Figure 3a). The pattern of greatest improvement for diadromous species may not hold in the Humber River which was not included in the present study because a complete barrier assessment has not been completed on it. Within the Humber River barrier mitigation has focused on restoring habitat for Brook Trout (*Salvelinus fontinalis*) in the headwaters. Brook Trout are a potadromous cold water specialist species that are rarely found in higher order streams or near the mouth of rivers in Southern Ontario.

Relatively few instream barrier mitigation projects occurred in the Etobicoke, Highland, and Mimico creeks, likely because of relatively few restoration opportunities. Etobicoke Creek has PIC values ranging from less than 10% in the northern reaches to greater than 50% in the south, Highland Creek has a PIC of over 50%, and Mimico Creek has a PIC of 57% (Table 1). High PIC values combined with large zones of urban land use, low habitat quality, and a lack of historical migratory salmonids has resulted in low conservation value and fewer restoration opportunities within these three watersheds. The negligible improvements in connectivity can also be attributed to the opportunistic approach of past restoration projects. Historically, balancing socio-economic and ecological values has been difficult as there is no systematic, repeatable decision-making strategy in place that can efficiently target the most important barriers to fish passage (Arponen et al., 2010). The maps of DCIs for the Etobicoke, Highland, and Mimico (Figure 3) show that improvement in connectivity has occurred in small, disconnected stream segments and connectivity has decreased in some sections of the Etobicoke since 1987. The lack of broad-scale improvement in connectivity demonstrates that the planning stages of restoration projects are critical to the overall benefit provided to aquatic communities. The Toronto RAP represents one of the early attempts to use a systematic method to protect and restore ecosystem functions. Techniques that provide quantifiable and easily repeatable results (Such as DCI) clearly identify where past restoration efforts have had the greatest impact to aquatic connectivity. By utilizing these techniques along with a systematic decision-making process in the future, instream barriers can be prioritized for removal so that aquatic connectivity can be improved in the most efficient manner for all fish species.

Conclusions

In addition to connectivity, future work should consider the impact barriers have on habitat quality and type. Barriers can alter habitat quality by impounding water, transforming lotic systems to lentic systems, increasing water temperature, increasing sedimentation, and all of which can lead to changes to the aquatic community (Ellis and Jones, 2013; Birnie-Gauvin et al., 2017). For restoration programs to be effective and meet their overall goals habitat quality and type must be considered as well.

There have been quantifiable, albeit minor improvements to aquatic connectivity in the five measured watersheds across the GTA. A large number of instream barriers have been mitigated since 1987, but many barriers still remain. The patterns represented by instream barrier mitigation project locations reveal an emphasis on conserving high quality habitat and restoring connectivity specifically for salmonids. Overall, aquatic connectivity is still extremely low in many GTA watersheds and more strategic conservation and restoration work must be done to improve these systems further. To improve connectivity for all species and remove future barriers in the most efficient manner, a prioritization scheme needs to be created that encompasses both quantifiable techniques like the DCI and expert biological knowledge. By combining old strategies with new, future decisions can be more effectively made to improve both fish community health and habitat quality.

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